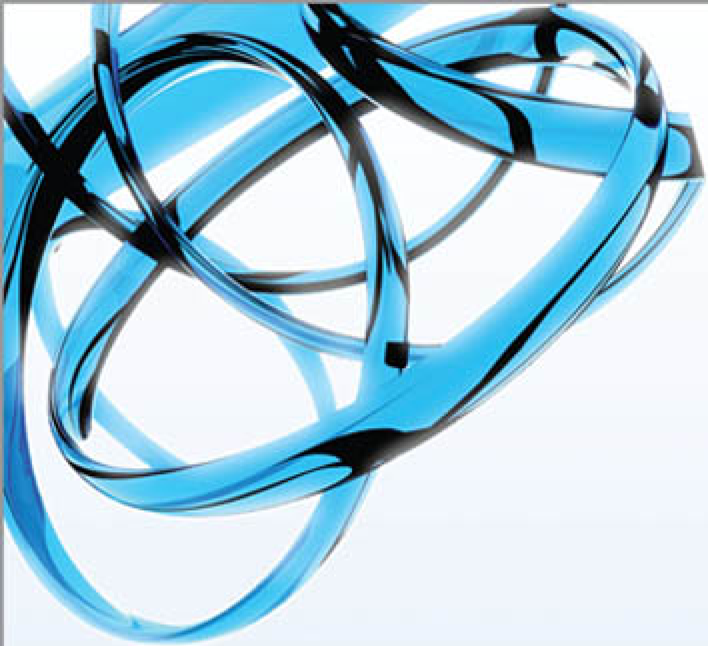

WATER WELLS AND PUMPS

A. M. MICHAEL
S. D. KHEPAR
S. K. SONDHI

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SECOND EDITION

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To

The cause of Efficient and Economical Use of Water Resources

for

IRRIGATION AND WATER SUPPLY
in the
DEVELOPING WORLD

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Preface to the Second Edition

Efficient and economical use of ground and surface water, using state-of-the-art equipment and technology, is of great importance in the present day development scenario. *Water Wells and Pumps* is a comprehensive treatise intended to serve as a basic reference to professionals and scientists working in the areas of irrigation, drainage, water supply, agriculture, ground water development, public health engineering, and rural development in government and non-government sectors. It will also serve as a reference for students of agricultural engineering, water resources engineering, civil engineering, environmental engineering, public health engineering, and urban and rural water supply and sanitation as well as management institutes, polytechnics, land and water management institutes, and staff training colleges of banks.

For the past two decades the book has enjoyed the status of an authoritative work on the subject. The present edition is revised and updated with emphasis to the subject areas of wells and pumps, including theory and applications. It lays particular emphasis to meet the specific socio-economic situations in India and other developing countries.

The book has been divided into two parts with seven chapters each. The first part **Wells for Irrigation and Water Supply** comprises of (i) Water Resources Development and Utilization, (ii) Hydraulics of Wells, (iii) Open Wells, (iv) Tube Wells and their Design, (v) Tube Well Construction, (vi) Development and Testing of Tube Wells, and (vii) Rehabilitation of Sick and Failed Tube Wells. The second part **Pumps and Pumping c**omprises of (i) Man and Animal Powered Water Lifts and Positive Displacement Pumps, (ii) Variable Displacement Pumps and Accessories, (iii) Centrifugal Pumps: Design, Installation, Operation, Maintenance and Troubleshooting, (iv) Deep Well Turbine and Submersible Pumps, (v) Propeller, Mixed Flow and Jet Pumps, (vi) Application of Non-Conventional Energy Sources in Pumping, and (vii) Techno-Economic Evaluation of Projects on Wells and Pumps. The discussions on each topic range from basic to most advanced areas. A large number of illustrations, tables, solved examples and problems have been included to facilitate easy understanding of the subject matter. There is a comprehensive coverage on various geo-hydrological formations, and influence of geographical situations and climate on ground water availability and quality to provide the necessary information required for selection of location, design and construction of tube wells and open wells for irrigation and water supply. Aquifer characteristics and basic equations governing ground water flow as well as legal aspects of ground water extraction and utilization, including water quality criteria for drinking water and irrigation have also been elaborately presented. Further, this new edition discusses open wells in hard rock, semi-consolidated, and unconfined formations, including their location, design, construction, operation and maintenance, along with procedures for deepening and boring of open wells and sanitary protection of open wells and tube wells. The chapter on rehabilitation of sick and failed tube wells is a unique attempt and provides specific details on the subject. The treatment on *pumps and pumping* provides detailed information on the various types of water lifts and pumps for irrigation and water supply, including their types and design, characteristics, adaptability, installation procedures, maintenance, advantages and limitations. Application of modern economic theories on the techno-economic evaluation of projects on wells and pumps are presented with a view to provide the required information for planning of projects. Short answers and objective type questions are provided at the end of each chapter to test the in-depth knowledge of students and candidates appearing for competitive examinations.

The authors acknowledge Er. B.S. Sidhu, Director Agriculture, Punjab, for providing the photograph for the cover. Every effort has been made to acknowledge the sources of information included in the book, wherever applicable. Omissions, if any, are inadvertent and will be rectified when pointed out. The authors welcome the suggestions of readers for improvements in the book.

A. M. Michael
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Preface to the First Edition

The major limiting factor in the economic and efficient utilization of ground water for irrigation and water supply has been the inadequate application of appropriate technology in this area. Water well and pump technology is yet to receive its due place in minor irrigation and water supply programmes in India and other developing countries. The result has been heavy expenditure on these projects and inefficient operation of both the well structure and the pumping system. The successive five year plans in India have been laying increasing importance to the development of irrigation potential to cover millions of hectares of land by ground water through wells and pumps. The Government has also launched a massive programme of rural water supply to provide potable water in every village in the country within the shortest possible time. This book is intended to provide the needed technology in these vital areas in national development.

Water Well and Pump Engineering presents a comprehensive treatment of the theory and practice of water wells and pumps for irrigation and water supply. It is intended as a basic text for students of agricultural engineering degree programme. It will also serve as a valuable text/reference to public health, civil, and mechanical engineering students and to students of agriculture and geology as well in-service trainees of professional organizations and institutions in ground water development, irrigation water management, public health engineering and rural development.

In addition to student readership the book will be a valuable reference to engineers and scientists working in the area of ground water development and utilization in irrigation and water supply. The section on river and canal pumping provides the technology for the utilization of this usually under-exploited resource. The treatment on techno-economic evaluation of water wells and pumps is intended to establish the credit-worthiness of projects proposals on the subject. The book is intended primarily to meet the requirement of students and practising professionals in India and other developing countries.

This book comprises three parts. Part I provides the technology for the design, construction, operation and maintenance of water wells for irrigation and water supply. Part II presents the application of electric motors and diesel engines in water pumping. The treatment on pumps and pumping, including the application of non-conventional energy sources in pumping, is included in Part III. It also includes a comprehensive treatment on techno-economic evaluation of projects on wells and pumps.

Each topic on wells and pumps has been discussed with the help of self-explanatory diagrams. A large number of solved examples have been included to facilitate the application of the principles to solve field problems. For additional practice, many unsolved problems along with answers have been appended with each chapter. Metric units of weights and measures have been used throughout the text. Tables, figures and articles are numbered chapterwise. A list of important references is given for each chapter to establish authority and to assist the student who may wish to verify or read more deeply into any particular area. Further than this, citations from the exceedingly voluminous literature are not attempted.

We are deeply indebted to many individuals and organizations for the supply of useful material for inclusion in this book and the assistance provided at various levels for the preparation of the manuscript. Every effort has been made to acknowledge the material received/adapted from different sources. Any omission therein is inadvertent and will be rectified in the subsequent reprint of the book, if pointed out by any one. We would welcome suggestions from the readers to improve the text.

A. M. MICHAEL
S. D. KHEPAR

Contents

1

Ground Water Resources Development and Utilization

Ground water has been a source of drinking water and irrigation since the dawn of recorded history. It is the most important of natural resources because of the physiological needs of man, animal and plant. It not only supports life on earth, but also governs the economic, industrial and agricultural growth of a nation.

The many uses of water—agricultural, domestic, industrial, pollution control, recreation, maintenance of aquatic life, power generation and navigation—are all related to the economic, mental and physical health of the world's population. Water is required not only in sufficient quantity, but of potable quality to live a healthy life. Water, whether in plenty or inadequate can cause diseases, especially in areas where people congregate. It is estimated that in the developing countries three out of five people have no access to safe drinking water and only one in four has any sanitary facilities.

Amongst the different components of the water resources of a nation, ground water is the most widely distributed, dependable and pure. Ground water irrigation provides for the maximum control on the supply of irrigation water to precisely meet the requirements of crops. It enables adoption of a diversified cropping pattern to maximise production from a given area in a given time. If the water bearing formation provides water from small voids and water movement is by intergranular flow, such as in sands, natural filtration takes place and, after a passage of about 15 m, all pathogenic bacteria generally get removed and the water can be used untreated. However, in hard rock wells, where water is transmitted through fissures, no filtration takes place and pathogenic bacteria can be transported rapidly over long distances. Hence, supplies from such sources are never totally safe without disinfection. A major problem with ground water is the possibility of pollution. This can originate from solution of the source rock itself or from artificial sources such as industrial wastes, fertilizers, pesticides or seepages from pit latrines and dumping pits.

Ground water development is usually through open wells in hard rock regions and tube wells in alluvial formations. Open-cum-bore wells are often employed to increase the yield of wells in water scarcity areas. In almost all cases, except when artesian conditions exist, ground water is to be lifted by human or animal power, mechanically operated pumps or through devices operated by non-conventional energy sources. Pumping from streams, rivers and canals usually offer an under-exploited resource for irrigation and domestic water supply in the developing countries.

1.1 THE HYDROLOGIC CYCLE

The total amount of water contained in the earth is constant and can neither be increased nor decreased. However, the availability of water for the use of man is dependent on the earth's unending moisture cycle known as the *hydrologic cycle*. It comprises a gigantic distillation system operating in and on the land and water bodies of the earth, and in the atmosphere surrounding it, with energy derived from the sun. Moisture is constantly circulating between the land, ocean and atmosphere. This complex series of phase changes and inter-connected flows is shown schematically in Fig. 1.1. The cycle has neither a beginning nor an end. The concept of the hydrologic cycle commonly begins with the water of the oceans, since it holds the bulk of the water of the planet. Radiation from the sun evaporates water from the oceans to form water vapour. The water vapour rises and collects in the atmosphere to form clouds. The circulation of moisture from the ocean to the land is influenced by the winds, atmospheric pressure differences, physiography of the continents, temperature differences and other factors. Under certain conditions, the cloud moisture condenses and falls back to the earth as precipitation (rain, hail, sleet or snow). Precipitation reaching the earth's surface may be intercepted by vegetative material, infiltrate into the ground, flow over the land surface as runoff or evaporate. Evaporation may be from the surface of the ground, free water surface, or leaves of plants (through transpiration).

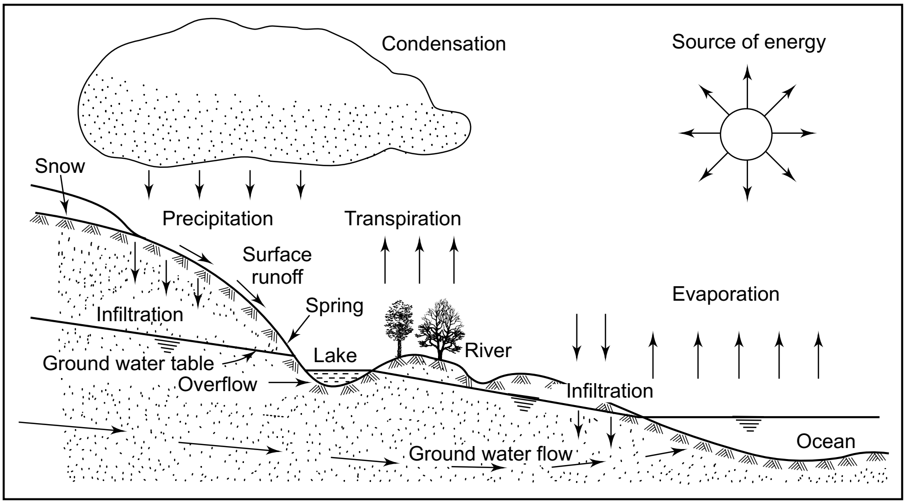

Fig. 1.1 Schematic diagram illustrating the earth's water cycle—the hydrologic cycle

A part of the precipitation, after wetting the foliage and ground surface, runs off over the land to streams, rivers and oceans. Another part infiltrates into the soil. Much of the water that enters the soil is detained in the plant root zone and is eventually drawn back to the surface by plants or soil capillarity, and returns to the atmosphere by evaporation or plant transpiration. Some of it, however, percolates below the plant root zone and, under the influence of gravity, continues to move downward until it enters the ground water reservoir. On joining the body of ground water, the percolating water may move through the pores of saturated subsurface materials and reappear at the surface, in areas at lower elevations, as subsurface flow. The ground water discharges naturally at such places, in the form of springs and seeps which maintain the flow of streams in dry periods. The streams, carrying both surface and subsurface flows, join the rivers and eventually flow back to the oceans.

In the hydrologic cycle, the soil acts as a reservoir; water is always in transitory storage in the soil. Considerable period of time may elapse before this stored water flows underground to the stream or is returned to the atmosphere by evaporation. Eventually, however, all water temporarily stored in the soil must enter the transitory part of the hydrologic cycle by percolating to underground storage reservoirs or reaching streams and rivers through subsurface flows and ultimately, the evaporation component of the hydrologic cycle. The hydrologic cycle is not always punctual. Delays and shortages in precipitation may therefore give rise to problems of water scarcity and drought. Even though man cannot influence the hydrologic cycle directly, there are many opportunities to increase the rainfall contribution to ground water.

1.2 TYPES OF WATER-BEARING FORMATIONS

An understanding of ground water occurrence requires a study of the vertical distribution of water in subsurface geologic formations. The earth's crust is called the lithosphere. It is composed predominantly of rock, consisting of disintegrated rock materials such as granite and sandstone. The lithology of a section through the earth's crust reveals the kind of rocks that occur in a succession of layers of strata below the surface, that make up any part of the lithosphere.

The outer part of the earth's crust is usually porous to varying depths, at different places. This is the zone of rock fracture. The pores or openings in this part of the lithosphere may be partially or completely filled with water. In the surface strata, the openings are only partially filled with water. This strata is called the *zone of aeration*. The layer below this, where the openings are completely filled with water, is called the *zone of saturation* (Fig. 1.2). The zone of aeration is divided into three zones—the soil water zone, the intermediate zone and the capillary fringe. The zones vary in depth and their limits are not sharply differentiated by differences in physical properties of earth material. A gradual transition exists from one zone to another.

Formations or strata within the saturated zone below the ground surface, from which ground water can be obtained for beneficial use, are called *aquifers*. *Ground water reservoirs or water-bearing formations* are the other terms commonly used instead of aquifer. These are permeable geologic formations that permit appreciable amounts of water to pass through them. Most aquifers extend over large areas and may be visualized as underground storage reservoirs. The thickness of the zone of saturation varies from a few metres to hundreds of metres.

The portion of the rock or soil not occupied by solid material may be occupied by ground water. These spaces are known as voids, interstices, pores or pore spaces. The porosity of a rock or soil is a measures of the void space between particles. It is the ratio of void space to the total volume of soil or rock. Expressed as percentage,

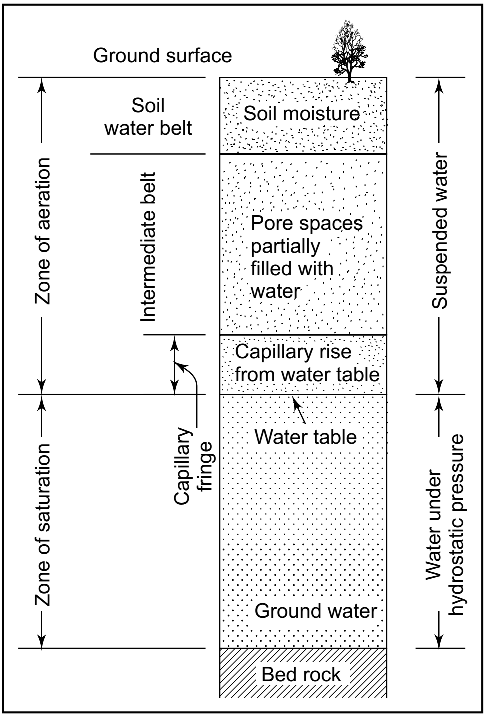

Fig. 1.2 Schematic sketch illustrating soil moisture and ground water

$$p = \frac{V_\omega}{V} \times 100 \tag{1.1}$$

where, p = porosity, per cent

V_ω = volume of entire pore space, cm^3 (or m^3)

V = total volume of rock or soil, cm^3 (or m^3)

The size of the pores and the total pore space of an aquifer vary with the type of formation material. Individual pores in a fine-grained material like clay are extremely small, but the total pore space is usually large. While a clay formation has large water-holding capacity, water cannot move readily through the tiny pores. It is hence not an aquifer even though it may be saturated. On the other hand, a coarse material such as sand contains large pores through which water can move fairly easily. A saturated sand formation is, therefore, an aquifer since it can hold water and transmit it at a satisfactory rate when pressure differences occur.

Water enters a ground water reservoir from natural or artificial recharge. It flows out under the action of gravity or is extracted by wells. Ordinarily, the annual volume of water removed or replaced represents only a small fraction of the total storage capacity of the aquifer.

1.2.1 Unconfined Aquifer

An unconfined aquifer (Fig. 1.3) is a permeable bed, only partly filled with water, and overlying a relatively impervious layer. Its boundary is formed by a free, water table or phreatic level. It is also known as a free, phreatic, water table or non-artesian aquifer. The water in a well penetrating an unconfined aquifer does not, in general, rise above the phreatic level (Fig. 1.3).

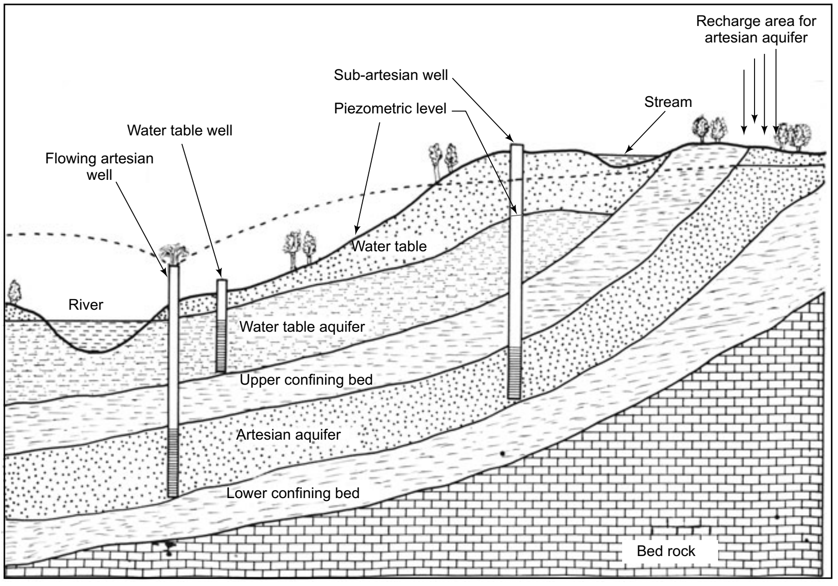

Fig. 1.3 Diagram illustrating artesian and water table aquifers, water table well, flowing artesian well, sub-artesian well and potential recharge area for the artesian aquifer

The upper boundary of the zone of saturation is called the water table. At the water table, the hydrostatic pressure is equal to the atmospheric pressure. The hydraulic pressure at any level within a water table aquifer is equal to the depth from the water table to the point. It is referred to as the hydraulic head. When a well is dug in a water table aquifer, the static water level in the well stands at the same elevation as the water table.

In general, the shape of the water table tends to follow the topography of the ground surface. It is, however, not a stationary surface, but rises or falls with the addition or withdrawal of water. Obviously, it would rise during the rainy season and fall during periods of drought.

1.2.2 Confined Aquifer

The zone of saturation may consist of permeable, impermeable and semi-permeable earth materials. An aquifer found between two impermeable layers is said to be *confined* (Fig. 1.3). It is also called an *artesian aquifer*. Because of the presence of an upper confining layer, the water in the pores of a confined aquifer is not open to atmospheric pressure, but is at a greater pressure.

When a well is drilled into a confined aquifer, water rises in it to a level above the aquifer, depending on the pressure of water in it. The elevation to which the water level rises is called the *piezometric level*. An imaginary surface representing the hydrostatic pressure in a confined aquifer is called the *piezometric surface*. The piezometric surface is analogous to the water table in an unconfined aquifer. The hydrostatic pressure within a confined aquifer is sometimes sufficiently large to cause the water to rise in a well and flow out, resulting in a flowing artesian well.

1.2.3 Semi-Confined Aquifer

A semi-confined or leaky aquifer is a completely saturated aquifer that is bounded above by a semi-pervious layer and below by a layer that is either impervious or semi-pervious. A semi-pervious layer is defined as one that has a low, though measurable, hydraulic conductivity. The elevation to which the water level rises in a well that taps a semi-confined aquifer is refered to as the piezometric level. The piezometric level is the same as that of a phreatic water table before pumping. Lowering of the piezometric head in a semi-confined aquifer, for example by pumping, will generate a vertical flow of water through the semi-pervious layer into the pumped aquifer. Hence, unlike confined and unconfined aquifers, two types of hydraulic heads are developed. They are the phreatic head above the semi-pervious layer lying over the main aquifer, and the piezometric head in the main aquifer. The piezometric head is always more than the phreatic head. The ratio of the heads depends on the hydraulic conductivity and the thickness of the semi-pervious layer.

In semi-confined aquifers, when the phreatic level is lowered almost simultaneously with the lowering of the piezometric level, the aquifer is called a *semi-confined aquifer with prompt yield*. When there is a significant time lag between the lowering of the two water levels, the formation is called a *semi-confined aquifer with delayed yield*.

1.2.4 Perched Water Table

A special case of a localized water body in an unconfined aquifer is the perched water table (Fig. 1.4). It is a body of water which has been retarded in its downward movement by a layer of earth materials at some distance above the water table. The impermeable layer is small in a real extent. The upper surface of the ground water in such a water body is called a *perched water table*.

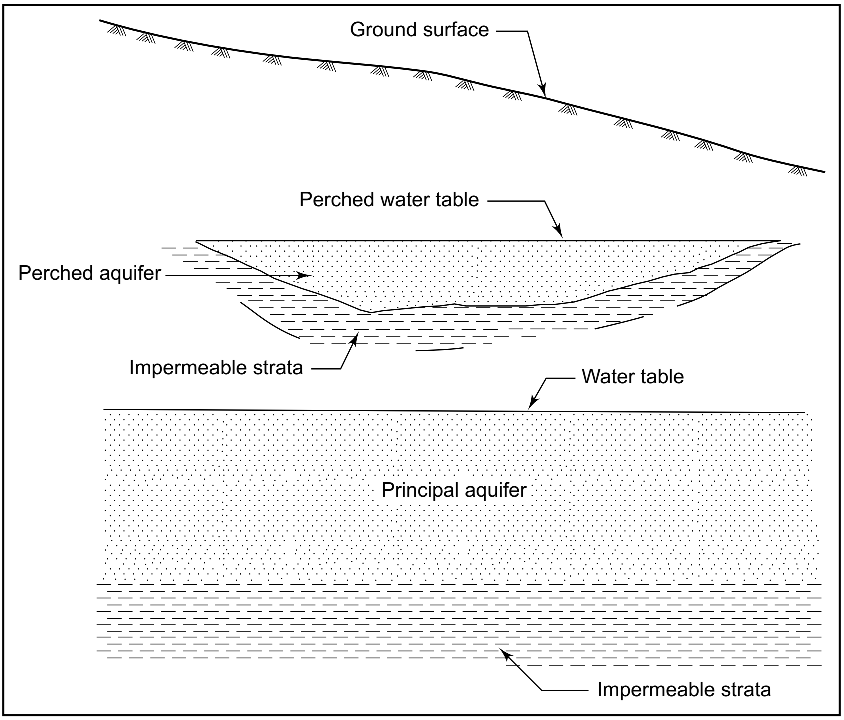

Fig. 1.4 Illustration of perched water table

1.3 TYPES OF SOIL WATER

Water can be present within soils and rocks in gaseous, liquid and solid phases. It can be present within certain crystal lattices or adsorbed on the outer surfaces of certain molecules or soil particles. In the unsaturated zone, the different types of water may be classified as hygroscopic water, capillary water and gravitational water.

1.3.1 Hygroscopic Water

The water which is held tightly to the surface of soil particles by adsorption forces. It is not available for use by plants.

1.3.2 Capillary Water

Water held by surface tension to soil particles, thus forming a continuous film (a few microns thick) around particles in void spaces.

1.3.3 Gravitational Water

Gravitational water is free water within the voids which moves downwards, under gravity, from the soil zone, through the intermediate zone, and to the zone of saturation, where it is termed as *ground water*.

Immediately above the zone of saturation extends the capillary fringe where water is held by surface tension to the rock particles or walls of fissures, joints or fractures. The height of the capillary fringe is related to the effective size of the void spaces. The capillary fringe may be several metres above the water table in clays, or as low as a few centimetres in sands.

1.4 HYDROLOGIC UNITS

1.4.1 Water Courses

Water courses are hydrologic units that include both surface and ground water, i.e. the water in a stream channel plus the ground water in the alluvium that underlies the channel and forms the bordering flood plains. Large quantities of ground water are pumped from water courses. Many wells are so situated that the water pumped from them is readily replaced by infiltration from the river, and their yield is exceptionally large. High permeability of the aquifer throughout the route, from river channel to well, is a prerequisite for successful wells. Water courses may offer excellent opportunities for large ground water supplies at some places, whereas at other places the alluvium is predominantly of fine texture and will yield only meagre supplies.

1.4.2 Abandoned Valleys

Abandoned valleys are no longer occupied by the streams that originally formed them. The abandoned valley may resemble a water course in respect of the permeability of materials and the quantity of ground water storage. However, the recharge and, therefore, the capability of high perennial yields are not likely to be as great as in those valleys which are occupied by streams.

1.4.3 Plains

Extensive plains flank the highlands or other features in many regions that were the source of their sediment. Sand and gravel beds form important aquifers under these plains in some places; but they can be relatively thin or discontinuous and not very productive in other places.

1.4.4 Intermontane Valleys

Intermontane valleys are similar to alluvial plains in that they may be underlain by large volumes of unconsolidated rock materials derived from the erosion of mountains. However, these materials are in separate basins bordered by mountain ranges. The coarser sediments are deposited by the larger tributaries close to the mountain flanks. Sand and gravel beds are the aquifers in intermontane valleys. They are of great economic importance and produce a major part of the ground water in most countries.

1.5 MINERALS AND ROCKS

The crust of the earth consists of different types of rocks which are composed of one or more mineral elements or chemical compounds. Common rock-forming minerals are quartz, calcite, feldspar, hornblende, mica and chlorite. The different types of rocks are arranged in groups, according to the manner in which they are formed.

1.5.1 Rocks

The term ‘rock’ is usually used by geologists to denote all materials of the earth, whether consolidated or firm or unconsolidated and loose or soft. Rocks are generally classified as sedimentary, igneous and metamorphic. The geologic structure, lithology and stratigraphy of rocks influence their potential as an aquifer.

Magmatic rocks have oozed out in molten (magma) from the interior of the earth and crystallized. If the magma has solidified slowly under high pressure at great depth, rocks with relatively large crystals are formed, e.g. granite. When the magma has penetrated higher up, in crevices or to the surface of the earth, in the form of lava, it cools more quickly and forms fine-grained rocks such as basalt.

Sedimentary rocks have been formed by weathered material, from the solid crust of the earth, which has disintegrated and sedimented at river mouths and on the beds of prehistoric seas. Examples of sedimentary rocks are sandstone, shale and limestone.

Metamorphic rocks are formed from eruptive or sedimentary rocks. The influence of pressure or heat, or exchange of elements with the surroundings, has transformed their structure and composition. Earth stresses may be large enough to deform rocks. When the deformation occurs at great depths, most rocks yield by flowage. At shallower depths the rocks are fractured. Since every rock has been exposed to the natural erosion process within the zone of fracture, outcrops on the earth’s surface are traversed by cracks and fractures. Most cracks and fractures come under the group joints.

1.5.2 Limestone and other Soluble Rocks

Limestone and dolomite, composed predominantly of calcium and magnesium carbonates, constitute a good part of all sedimentary rocks. They vary widely in permeability. Some are relatively dense; others have appreciable porosity from the initial interconnecting pore space that remains in consolidated rocks. Many have developed permeable zones subsequent to their deposition.

1.5.3 Basalt and other Volcanic Rocks

Basalt, a dark-coloured volcanic rock that may spread as a sheet to form extensive plains, usually has comparatively good permeability. In general, the basalt flows are permeable, except for massive flows. Other permeable zones in these volcanic rocks include porous zones between successive lava beds, lava tubes, shrinkage cracks and joints.

1.5.4 Crystalline and Metamorphic Rocks

These occur chiefly in mountainous areas, or in areas that have been mountainous in past geologic ages. They are poor water bearers. Where these rocks are close to the surface in humid regions, they yield small but reliable water supplies. Water occurs in the partially weathered rocks near the surface, and this zone may extend to depths as great as 30 m. Most wells in these rocks yield supplies sufficient only for domestic use.

1.5.5 Sandstone and Conglomerate

Sandstone and conglomerate are the consolidated equivalents of sand and gravel. They differ from the latter chiefly because of the presence of cementing materials between the grains of pebbles. The porosity has been reduced by the cement, and many of the rocks are thoroughly cemented to yield any appreciable quantity of water.

1.6 INFLUENCE OF PHYSIOGRAPHY AND CLIMATE ON GROUND WATER AVAILABILITY

The origin, distribution and utilization of the water resources of any country are profoundly influenced by its physiography, climate and soils. The Indian subcontinent lies between 8°4′ and 37°6′ North latitude and 68°7′ and 97°25′ East longitude, covering an area of 328 million hectares. India has a land frontier of 15,290 km and a coastline of 5,700 km. The diversity of landforms is matched by the diversity of climate, people and cultures. Towering mountain ranges, rolling hills, lofty plateaus and extensive plains have all played major roles in shaping the physical features of this great country and the cultural, economic and political history of its people.

India is a vast country with diversified geological, hydrological, hydrometeorological and geomorphological settings. Variations in the nature and compositions of rock types, geological structures, geomorphological setup and hydrometeorological conditions have correspondingly given rise to widely varying ground water conditions, thereby resulting in varying conditions for well drilling in different parts of India. In the high-relief areas of the northern and north-eastern regions occupied by the Himalayan ranges, the various conspicuous hill ranges of Rajasthan and the central and southern Indian regions, the presence of steep land slopes and geological structures offer extremely high run-off. Thus, there is very little scope for rain water to find favourable conditions for storage and circulation as ground water. The large alluvial tract, extending over 2,000 km in length from Punjab to Assam, often referred to as the Sindhu-Ganga-Brahmaputra plains, is the most potential and important region in India from the standpoint of ground water resources.

Almost all of central and southern India is occupied by a variety of hard rocks with hard sediments (including carbonate rocks) in the intertectonic and major river basins. Rugged topography, the hard and compact nature of the rock formations, geologic structures and meteorological conditions have yielded an environment which allows ground water to store itself in the weathered formations and circulate through the underlying fracture systems. In hard-rock terrains, the river valleys and abandoned channels, wherever they have sufficient thickness of porous materials, act as potential areas of ground water development on an intensive scale under favourable hydrometeorological conditions.

The coastal and deltaic tracts, particularly of the east coast, are covered with vast and extensive alluvial sediments. Though the tracts are highly productive in terms of water supply, the overall ground water regime in the vicinity of the coasts suffers salinity hazards. Ground water development efforts in the coastal fringe area have to regulate withdrawals in such a manner that contamination of the fresh ground water by the saline ground water body is avoided.

1.6.1 Rainfall

The major source of water available, either for agriculture or human consumption, is obtained from the rain that falls on the earth's surface. India has a monsoon-dominated rainfall pattern. The south-west monsoon, north-east monsoon, cyclonic depressions and local storms contribute to rainfall in different degrees in the various rainfall regions of India. An outstanding feature of the wind system over the Indian ocean and the adjoining sea and land areas is the seasonal reversal of the *monsoons*. (The monsoon is the periodic wind of the Indian ocean, which is south-west from April to October and north-east during the rest of the year).

About 80 per cent of the rainfall in most parts of India is contributed by the south-west monsoon. This is confined mainly to four months, namely, June to September. The rainy-season crop, known as the *kharif* crop in most parts of the country, is mainly dependent on the south-west monsoon rains. Figure 1.5 shows the mean annual rainfall in India.

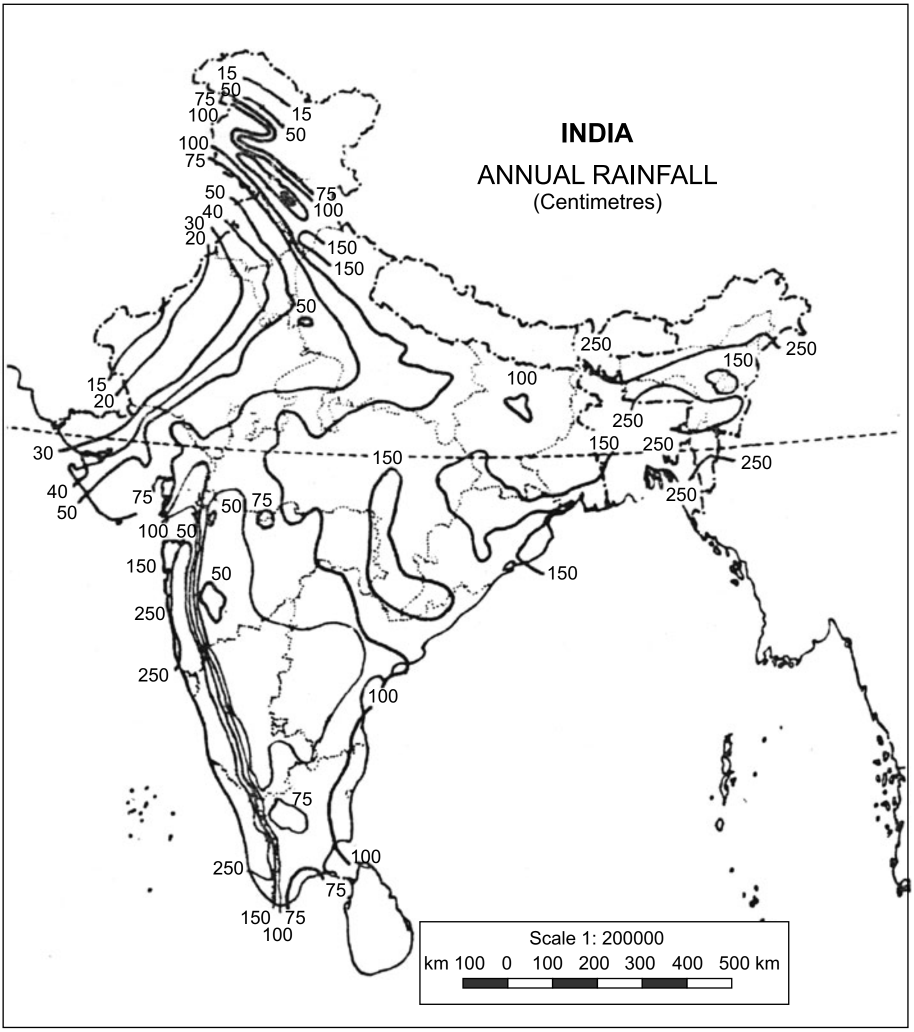

Fig. 1.5 Map of India showing average annual rainfall

1.7 HYDRO-GEOLOGICAL FORMATIONS

Ground water availability in a formation is largely governed by the state of cementation and compaction of the formation. The geological formations encountered in India may be broadly divided into three categories, namely, unconsolidated, semi-consolidated, and consolidated formations. Figure 1.6 present the geographical distribution of ground water formations in India.

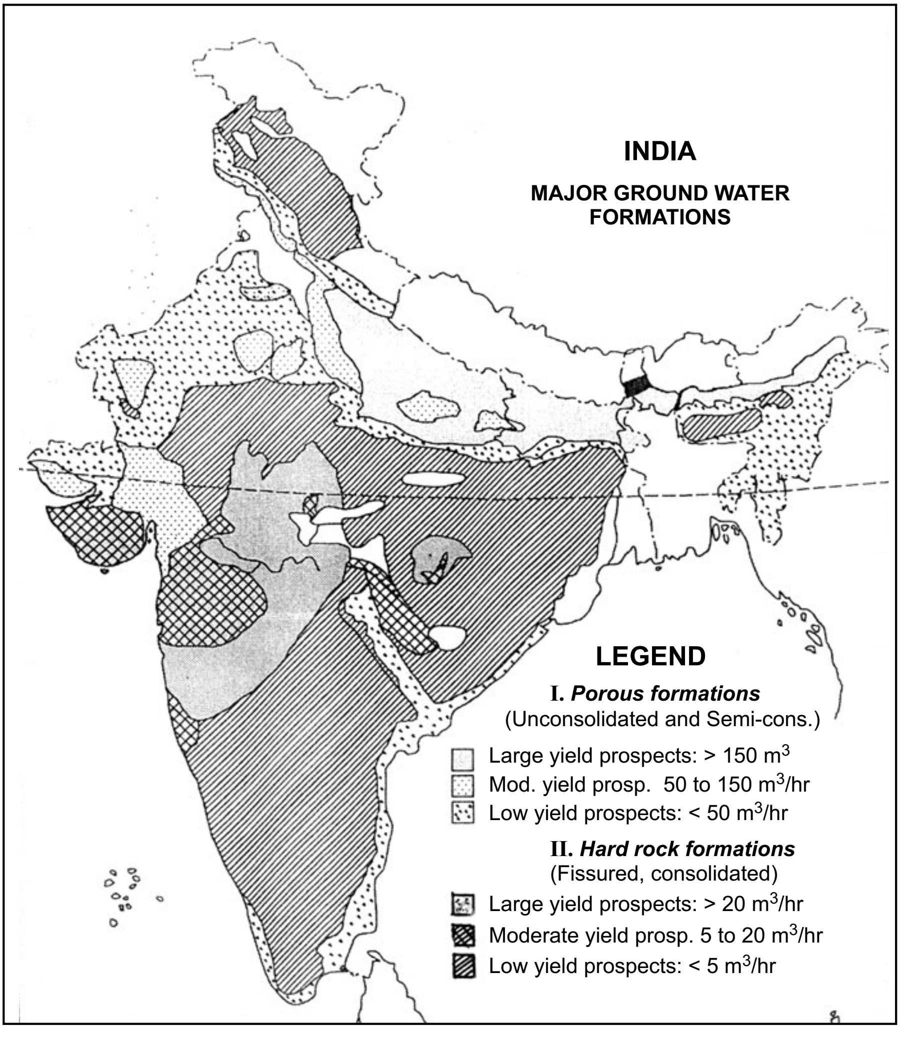

Fig. 1.6 Map of India showing major ground water formations

1.7.1 Unconsolidated Formations

Unconsolidated formations include the alluvial plains built up by the Himalayan rivers, namely, the Indus, the Ganga, the Brahmaputra and their tributaries; the inland valleys of the rivers Narmada, Tapti and Purna in Central India; the coastal alluvial plains of the East and West Coasts and the plains of Gujarat; and the aeolion sand-tracts of Western Rajasthan. These formations are rich in ground water, except in parts of the north-western arid and semi-arid zones not served by irrigation canals. They comprise about one-third of the total land area of India, but account for about 50 to 60 per cent of the total usable ground water resources. The lithology includes zones of sand, gravel, pebbles, etc., which not only store large quantities of ground water but are also favourable from the point of view of ground water extraction. The ground water productivity of unconsolidated formations is given in Table 1.1.

TABLE 1.1 Ground Water Productivity of Unconsolidated Aquifer Systems

Geological formation	Area	Aquifer type	Yield prospects (m^3/hr)
Piedmont Alluvial Plain (Bhabar zone)	Himalayan Foot Hill	Unconfined/ Confined	120 to 250
Tarai Alluvial Plain	Fringing Bhabar	Confined/ Unconfined	80 to 300
Ganga-Sindhu Alluvial Plain	Gangetic Trough	Unconfined	50 to 300
Brahamputra Alluvial Plain	Assam Valley	Unconfined/ Confined	50 to 300
Intermantane Valley	Dun, Paonta, Nalagarh Una Valley	Unconfined	50 to 200
Narmada Valley-fill	Narmada Basin	Unconfined/ confined	50 to 200
Tapi and Purna Valley fill	Tapi Basin Purna Basin	Unconfined/ Confined	10 to 50
Glaco-lacustrine Deposit (Karewa beds)	Kashmir	Unconfined/ Confined	200–350
Fluvioglacial	Ladakii	Unconfined	53
Coastal Alluvium	East-Coast	Unconfined	30 to 300
Laterite & Older Alluvium	Chotanagpur Plateau	Semi confined to confined condition	100

Source: Sharma (2001)

1.7.2 Semi-Consolidated Formations

These include the semi-consolidated sandstone formations of the Masozoics and Tertiary age, in different parts of the country, such as Western Rajasthan, Lathi Series and Palana and Nagpur sandstones; the East Coast, the Cuddalore sandstones and Rajamundry sandstones; the West Coast, the Varkalli formations in Kerala, the Himmatnagar sandstones, the sandstones of Bhuj and Katrol series in Gujarat; and the rocks of the Gondwana systems, which have sandstones and shales in Andhra Pradesh, Bihar and Orissa. The semi-consolidated formations are next in importance from the ground water availability angle, but hardly cover about 5 per cent of the total land area of India. The lithology is generally favourable for ground water storage and extraction. The ground water productivity of semi-consolidated formations is given in Table 1.2.

TABLE 1.2 Ground Water Productivity of Semi-consolidated Rock Aquifers

Geological formations	Area	Aquifer type	Yield prospects (m^3/hr)
Waikam beds	West-Coast	Unconfined/ Confined	50 to 180
Tipam Sandstone	Tripura Valley	Unconfined/ Confined	50 to 150
Naguar-Jodhpur Sandstone Limestone	Rajasthan	Unconfined/ Confined	15 to 75
Cuddalore Ariyalore	East-Tiruchirna Palli	Unconfined	20 to 100
	Pondicherry	Confined	15 to 80
	Karaikal		160
Himmatnagar Sandstone	Mehsana	Unconfined	10 to 100
Lathi Sandstone	West Rajasthan	Confined	100 to 500
Gondwana Sandstone	Damodar, Mahanadi & Godavari	Confined	20 to 50
Sandstone/Shales	Vidhyans	Unconfined/ confined	70 to 120

Source: Sharma (2001)

1.7.3 Consolidated Formations

The major part of India, including almost the entire Indian peninsula, consists of hard rock formations. These comprise crystalline rocks, granites, gneisses, schists, etc. of the Archean age; basaltic formations of the Upper Cretaceous to Oligocene age; and compact sedimentary formations, Cuddapah, the Delhi's and Vidhyan systems which belong to the Pre-Cambrian age. Nearly 65 per cent of the total land area in India is covered by hard rock formations, of which about one-fourth is accounted for by basaltic formations.

The rocks in consolidated formations have no primary pore spaces and hold limited quantities of ground water, contained in the weathered and the fractured zones. However, sizeable quantities of water are available at some locations in Vasicular lava flows, intertrappean beds and caverneous limestones. Table 1.3 presents the extent of hard rock areas and geological formations in Central and South India.

Hard rock is a general term used by hydrogeologists to terrain comprising largely of igneous and metamorphic rocks. They virtually have no primary porosity. However, they have a secondary porosity due to fracturing and weathering, which permits the flow and storage of ground water. The storage capacity of unweathered hard rocks is limited to the interconnected system of fractures, joints and fissures in the rock. Such openings are mainly the result of world-wide tectonic phenomena in the earth's crust. Weathering processes influence the storage capacity of hard rocks. Mechanical disintegration, chemical solution and deposition and the influence of climate and vegetation on weathering bring about local modification of the primary rocks and its fractures.

TABLE 1.3 Extent of Hard Rock Areas and Geological Formations in Different States of Central and South India

Name of state	Percentage of hard rock area	Geological formations and rock types
Andhra Pradesh	85	Traps—limestones, quartzites, granites, gneisses
Bihar and Jharkhand	43	Traps—granites, gneisses
Gujarat	50	Traps—quartzites, granites and gneisses
Karnataka	97	Traps—sandstones, limestones, quartzites, granites and gneisses
Kerala	93	Granites and gneisses
Madhya Pradesh and Chhattisgarh	80	Traps—limestones, quartzites, granites and gneisses
Maharashtra	94	Traps—granites and gneisses
Orissa	80	Limestones, quartzites—granites and gneisses
Rajasthan	35	Traps—limestones, quartzites, granites and gneisses
Tamil Nadu	73	Limestones, granites and gneisses

1.7.4 Influence of Weathering in Hard Rocks on Ground Water Availability

To provide for significant quantity of ground water in hard rock areas, the weathered layer must attain a minimal areal extent and thickness and have sufficient porosity to store water and permeability to permit its flow into wells. The thickness of the weathered layer and the presence of permeable zones are influenced by a number of factors including climate, topographic position, mineralogic composition and lithologic texture, and the distribution and spacing of fracture system in the host rock. The thickest weathered layers generally develop in sub-humid and humid tropical regions where vegetative cover is relatively dense and rainfall exceeds 1000 mm. Relatively thick weathered layers are also found in semi-arid regions. In the low-altitude regions of western Rajasthan, for example, the weathered layers may be as much as 25 to 30 m thick in areas where the annual rainfall may be as low as 380 to 460 mm. Topography and stage of geomorphic evolution are important factors influencing the development of a really extensive weathered layers. Between rock types, fine grained rocks are less susceptible to weathering than coarse grained rocks. The spacing and distribution of fracture systems have profound influence on weathering. In granite and other rock terrains, where the fracture systems are closely spaced (a few metres or less), weathering agents may penetrate deep into the host rock to form thick weathered layers with permeable zones. On the other hand, massive and poorly fractured granite resists weathering.

Thin weathered layers may not contain adequate water for exploitation. Locally, however, even relatively thin weathered layers may sustain perennial aquifers if there is a prevailing high recharge, either natural or artificial. In some irrigated areas of India, deep percolation from irrigated areas plus the normal rainfall recharge sustain wells in weathered layers which are only 5 to 7 m thick. In most places, however, weathered layers less than 10 m thick do not contain exploitable quantities of ground water. Many productive wells, where ground water has been developed for domestic supply and small scale irrigation, tap the water bearing layers of the weathered zone with average thickness of 10 to 20 m.

In some regions where the weathered layers are thin or absent, ground water may occur in the fracture system below and could be tapped by boring. Even thin weathered layers help in transmitting the infiltrated water from the surface to deeper fracture systems. In many situations it is possible for a well to tap ground water both from the weathered layer and from a deeper underlying fracture system, when water in the weathered layer becomes depleted during dry season. The ground water productivity of consolidated formations is given in Table 1.4.

TABLE 1.4 Ground Water Productivity of Fractured Rock Aquifers

Geological formations	**Area**	**Aquifer type**	**Yield prospects (m^3/hr)**
Basalt	Deccan Plateau	Unconfined	20 to 70
Basalt	Rajmahal trap	Unconfined/ Confined	10 to 60
Limestone	Raipur, Chattisgarh, Durg	Unconfined	50 to 180
Granite gneisses	Peninsular Shield	Unconfined	5 to 55
Crystalline	Peninsular Shield	Unconfined	5 to 100
Limestone, Schists and Phyllites	Peninsular Shield	Unconfined	10 to 20

Source: Sharma (2001)

1.8 GROUND WATER INVESTIGATIONS

A programme of ground water investigations is to obtain information on the resource through systematic collection, synthesis, interpretation and compilation of data. It seeks information on its occurrence, movement, storage, recharge, discharge, quality and quantity. It includes the study of its geological environment, as also the hydrologic and hydraulic aspects of its flow system.

There is some water under the earth's surface almost everywhere. Ground water exploration, however, means determining whether the water occurs under conditions that permit utilization through wells. It is essential to appraise the available ground water resource qualitatively as well as quantitatively. Knowledge of geological conditions and hydrologic parameters are important for the proper design and construction of open wells and tube wells.

A comprehensive programme for hydrogeological investigations may comprise the following activities:

1.8.1 Surface Investigations (*Covering Hydrogeological Aspects*)

(i) Geological field reconnaissance, including observations and collection of data from excavations, bore holes and wells. The appraisal includes information on geological factors, particularly tectonics, lithology, permeability, fissuring and outcrop area.

(ii) Geophysical surveys
   - (a) Electrical resistivity method
   - (b) Seismic refraction method

1.8.2 Subsurface Investigations of Ground Water

(i) Test drilling and preparation of lithological logs
(ii) Sub-surface/bore hole geophysical investigations:
  (a) Electric logging: resistivity and potential
  (b) Radiation logging: gamma ray and neutron
(iii) Collection of lithological and other logs of existing bore holes and correlation of lithological logs

1.8.3 Hydrological Investigations

(i) Preparing inventory of existing wells, giving their location, depth, depth of water, construction features, type of pumping equipment used, pumping records and water analysis
(ii) Study of ground water levels—preparation of water table contour maps, water level profiles, hydrographs and setting up of observation grids
(iii) Collection and analysis of water samples
(iv) Aquifer tests—to appraise transmissibility and storage property of aquifers
(v) Hydrologic appraisal of the geological framework: geometry of aquifers and boundaries affecting recharge and discharge of ground water
(vi) Correlation of stream-flow factors with ground water recharge and discharge
(vii) Estimation of seepage and recharge contribution from canals, lakes and ponds
(viii) Study and analysis of meteorological factors; precipitation and evapo-transpiration
(ix) Rainfall and infiltration studies to estimate contribution of rainfall to ground water recharge
(x) Hydrologic analysis of ground water systems through analytical and other techniques

Ground water investigations on a sizeable scale have been undertaken in India since the initiation of the Five-Year Plans in 1950–51. The emphasis, until a few years ago, had been on delineation and assessment of aquifers, mainly through geological and geophysical surveys and test drilling. Emphasis on hydrological aspects and resource evaluation studies were initiated in the seventies.

Several new techniques have been introduced in ground water investigations during the last few years in advanced countries. These include use of radioactive materials in tracing ground water movement, aerial photo-interpretation in hydrogeological studies, sophisticated bore hole geophysical methods including radioactivity, temperature, fluid conductivity and flow-meter logging. Techniques for automated data processing, using digital computers and numerical analysis, graphical (flow net analysis) and other analytical methods in solving ground water problems are being employed.

1.8.4 Water Divining

Water divining is the art of detecting underground water by means of an involuntary muscular reaction on the part of the practitioner. Generally, a pointer, such as a twig, metal rod or piece of wire is used. Nothing is precisely known about the basis of this art. Water diviners, where successful, have generally located small flows. However, water engineers do not depend on water diviners' recommendations as reliability of the method does not have adequate scientific justification.

1.8.5 Test Drilling

The most reliable method of identifying the character of aquifer and non-aquifer formations beneath the earth's surface is to drill test holes past them and obtain samples while drilling. *A well log* is a systematic record of the characteristic properties of the samples of subsurface materials obtained during the progress of drilling.

Test drilling is done to satisfy two objectives: (i) to explore the ground water resources of a region, and (ii) to obtain information on the geologic and ground water conditions of a well site prior to installing a regular well. Almost any well drilling method may be used for test drilling. However, in unconsolidated formations, cable tool and hydraulic rotary methods are the most common. The cable tool method is slower but provides more accurate samples from the bailer. The rotary method is faster but it is sometimes difficult to determine the exact character of the formation. This is particularly true where fine-grained materials are encountered, as they mix with the drilling fluid.

1.8.6 Geophysical Methods

Geophysical surveys provide direct evidence of the characteristics of subsurface formations with reference to their being aquifers or not. The methods do not measure the type of rock, its porosity, intrinsic permeability or mass density. They measure other properties of the formations which determine whether it may be adequately porous and permeable to satisfy the requirements of an aquifer.

Geophysical methods may be surface-type or bore-hole-type operations, depending on whether the measurements are done at or above the ground surface, or below the ground in drilled holes. The commonly used geophysical methods of ground water prospecting are the electrical resistivity method and the seismic refraction method.

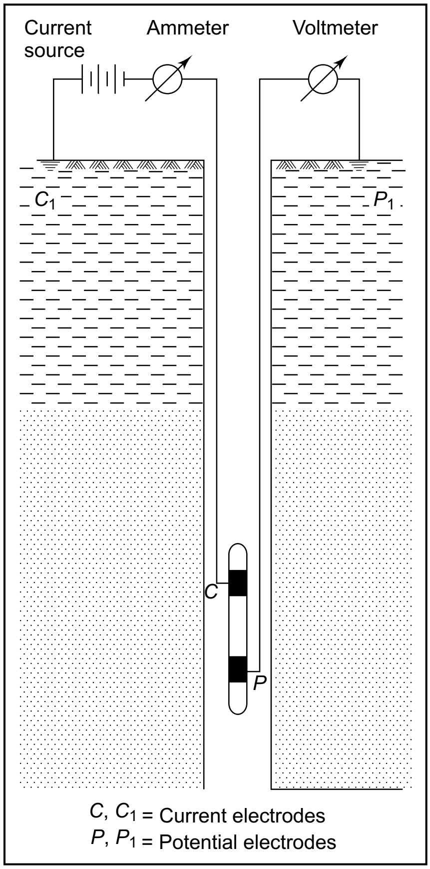

Fig. 1.7 Electrode arrangement and electrical circuits for the two-electrode logging procedure

Electrical Resistivity Method

Measurements of electrical resistivities of underground formations reveal certain specific aquifer characteristics. For instance, clean sand saturated with fresh water shows relatively high resistivity. A sandy layer containing clay shows a lower resistivity. By measuring the electrical resistivities of the two materials, the higher electrical resistivity of clean sand is interpreted to mean that it is a better aquifer than the sand having lower resistivity. Because various types of underground formations usually exhibit characteristic values of resistivity, strata of different materials can be broadly identified. Sands, gravels, and sandstones have high resistivity, compared to low resistivity materials such as clay and shales.

Electric Logging

A common bore-hole geophysical method is electric logging (Fig. 1.7). An electric log is a record of the apparent resistivities of underground formations and the spontaneous potentials generated in the bore hole, both plotted in relation to depth below the ground surface. These two properties are indirectly related to the characteristics of the formations and to the quality of ground water in them. The procedure is applicable only to uncased bore holes.

Many types of electrode arrangements are employed for electric logging. Instrumentation for electric logging varies from simple hand-operated portable equipment to truck-mounted and power-driven equipment. The type of equipment required depends on the depth of the hole and its diameter. For wells 300 to 1000 m deep, it is advantageous to have power-driven equipment. Shallow wells can be logged easily by manually operated portable equipment.

Interpretation of electric log data is influenced by the diameter of the bore hole, chemical quality of ground water, porosity of the formation and degree of mud intrusion into it, and the type of electrode arrangement used in the survey. An important variable in electric logging is the chemical quality of the ground water. The formation resistivity varies inversely with the dissolved solids content of ground water in the formation. A clean sand saturated with water having, say, 600 parts per million (ppm) dissolved solids, will show a formation resistivity about half that of the same sand containing water with 300 ppm dissolved solids.

Gamma-Ray Logging

Gamma-ray logging is based on measuring the natural radiation of gamma rays from certain radioactive elements that occur in subsurface formations. The log is a diagram showing the relative emission of gamma rays. The rays are measured in counts per second and plotted against depths below the surface (Fig. 1.8). The resulting curve is similar in appearance to the resistivity curve of an electric log.

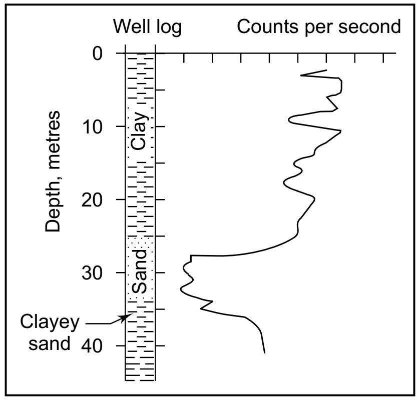

Fig. 1.8 Gamma-ray log and well log—a typical case

Equipment for gamma-ray logging is similar to that used for electric logging, except for the well probe and detecting device. Logs can be made using a suitable counter for the down-the-hole sensing unit. The counter at the ground surface converts the number of electric pulses per second, received from the probe, into voltages. The voltage is continuously recorded on a tape or film as the probe is pulled up the hole.

Gamma-ray logs can be obtained in cased and uncased wells. Thus, it can be used in situations where electric logging is not possible. Further, a gamma-ray log is not influenced by changes in water quality. So the log is valuable in identifying the position and thickness of clay formations where the alternating sand formations may contain saline water.

Electrical Resistivity Surveying

In electrical resistivity surveying, the measurements of earth resistivity are made from the ground surface. The relative values of electrical resistivity are interpreted in terms of the general geology of the subsurface to limited depths. Resistivity values are measured with four electrodes set in the ground. Electric current is applied to the ground through two of the electrodes and the potential drop across the other two is noted. A common arrangement is with the electrode equally spaced along a straight line (Fig. 1.9).

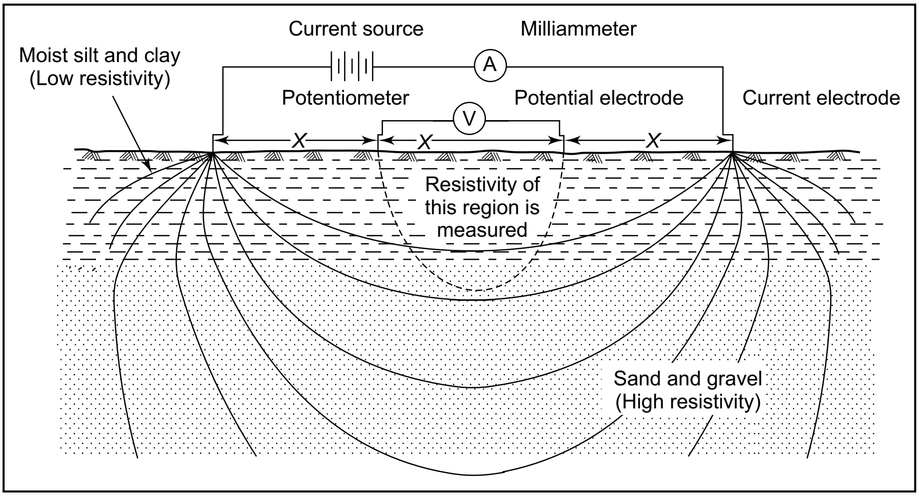

Fig. 1.9 Definition sketch illustrating prospecting of ground water by electrical resistivity method

The apparent resistivity is computed on the basis of the potential drop, the applied current, and the electrode spacing. In most instruments the ratio of the potential drop to the applied current could be read directly as resistance in ohms. This value is referred to as the apparent resistivity of the lithosphere, down to a depth proportional to the electrode spacing. Apparent resistivity is the weighted average of the real resistivities of the individual strata within the range of resistance measurement.

Seismic Refraction Surveying

Seismic refraction surveying is based on the principle of differential rates of travel of shock waves through different earth materials. In denser materials, the shock waves travel faster. From field measurements of differences in velocity, the existence of different layers of subsurface materials are identified. The method is suitable only where the velocity of the shock wave increases with depth.

Shock waves are produced by setting off an explosive charge in a shallow hole, or by striking the ground with a heavy hammer. A seismograph is used to detect the time of arrival of the shock wave over a measured distance from the point of application of the shock. The velocity of the first part of the shock wave is then calculated. Comparison of shock wave velocities measured at various distances between the shock point and detector instruments enables characterization of subsurface geologic formations.

1.9 GROUND WATER QUALITY

The quality of ground water is an essential factor in determining its suitability for water supply and irrigation. Surface water is often turbid and contains considerable quantities of bacteria, whereas ground water is often free of suspended matter and bacteria. Ground water is usually clear and colourless and is therefore, normally superior to surface water from sanitary considerations. Ground water, however, has higher salt content than surface water, as slow moving water remains in contact with the substrata for longer periods, increasing the soluble mineral content until a condition of equilibrium is reached.

Water, being a universal solvent, carries minerals in solution which, though present in small quantities, determine its suitability for various purposes. The quantity and composition of the dissolved minerals in natural water depend upon the type of rock or soil with which it has been in contact or through which it has percolated, and the duration it has been in contact with these rocks. The quality of ground water may vary from place to place and stratum to stratum. It also varies from season to season. The requirement of quality of water for various purposes, such as drinking, industrial use and irrigation vary widely. The determination of suitability of ground water would involve a description of the occurrence of the various constituents and their relation to the use to which the water would be put. The water quality data also provide information about the geologic history of rocks, ground water recharge, discharge, movement and storage.

1.9.1 Definition of Terms

Some of the important terms used in ground water quality are defined as follows:

Electrical Conductivity (EC)

This is the reciprocal of electrical resistivity. Quantitatively, electrical resistivity is the resistance, in ohms, of a conductor (metallic or electrolytic) which is 1 cm long and has a cross-sectional area of 1 cm^2. Hence, electrical conductivity is expressed as the reciprocal of ohm-centimetre, or mhos per centimetre. The term "electrical conductivity" and specific electrical conductance have identical meanings. The units commonly used for expressing electrical conductivity are as under:

Symbol	*Term*	*Unit*
EC	Electrical conductivity	mhos/cm
dS/m	Decisiemens/metre	10^{-3} mhos/cm

Leaching Requirement

The fraction of water entering the soil that must pass through the root zone in order to prevent soil salinity from exceeding a specified value.

Parts Per Million (ppm)

The results of a chemical analysis of water are usually reported in parts per million of the various substance present in the sample. One part per million (ppm) means one part in a million parts. As commonly measured and used, parts per million is numerically equivalent to milligrams per litre.

*p*H

The *p*H value of soil or natural water is a measure of its alkalinity or acidity. More accurately, the *p*H value is a measure of the hydrogen-ion concentration in water. Water molecules (H_2O) have a slight tendency to break down into ions. Ions are atoms or groups of atoms carrying positive or negative electrical charges. The chemical formula H_2O may also be represented as HOH. When a water molecule breaks down, it divides into a positive hydrogen ion (H^+) and a negative hydroxyl ion (OH^-). In distilled water, the concentration of H^+ ions formed is expressed by a *p*H value of 7. (Mathematically this is the logarithm, to the base 10, of the reciprocal of the hydrogen-ion concentration of pure water). Thus, a *p*H value of 7 indicates a neutral solution, neither alkaline nor acid. A *p*H value of 7.5 to 8 usually indicates the presence of carbonates of calcium and magnesium, and a *p*H of 8.5 or above usually indicates appreciable exchangeable sodium.

Total Dissolved Solids

The total dissolved solids in a water sample include all solid materials in solution, whether ionized or not. It does not include suspended sediments, colloids, or dissolved gases. The total dissolved solids is the numerical sum of all dissolved solids determined by chemical tests. In general, the total concentration of dissolved salts (TDS) is an indication of the overall suitability of water. The quality of water for drinking and irrigation diminishes as the value of TDS increases. Figure 1.10 presents the broad delineation of ground water quality in India.

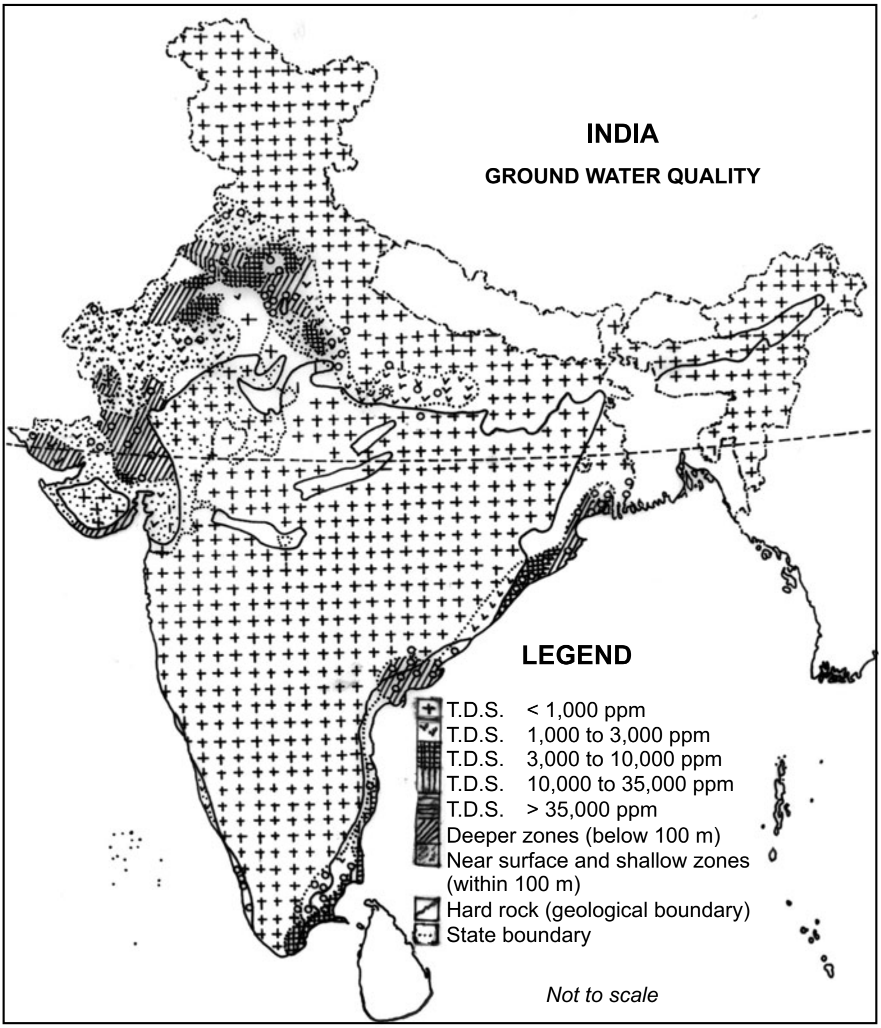

Fig. 1.10 Map of India showing quality of ground water (Based on data generated by Central Ground Water Board)

The more important constituents affecting water quality have been divided into two groups: major constituents and minor constituents. The major constituents are the cations—calcium, magnesium, sodium and potassium; and the anions—carbonates, bicarbonates, sulphates, chlorides and nitrates. These occur in most waters. These constituents form the bulk of the dissolved salts and determine, to a very large extent, the quality of the water, with the exception of boron and, rarely, one or two of the minor constituents. The minor constituents include boron, silica, fluoride, nitrite, lithium, sulphide, phosphate, iron, aluminium, ammonia, hydrogen ion (as measured by *p*H) and organic matter.

1.9.2 Quality Criteria for Drinking Water

The most undesirable constituents of drinking water are those capable of having a direct adverse impact on public health. Water intended for human consumption must be free from organisms and concentrations of chemical substances that may be a hazard to health. The appearance, taste and odour of drinking water should be acceptable to consumer. The acceptability of drinking water to consumers is subjective and can be influenced by many different constituents. The concentration at which constituents are objectionable to consume is variable and dependent on individual and local factors, including the quality of the water to which the community is accustomed and a variety of social, environmental and cultural considerations. The standards for drinking water prescribed by the World Health Organization is the most accepted international standard on the potability of water. In addition many countries have established national standards for drinking water. In India, agencies like the Indian Council of Medical Research (ICMR), Bureau of Indian Standards (BIS) and Central Public Health and Environmental Engineering Organization (CPHEEO) have formulated drinking water standards which are being followed by different authorities. Table 1.5 presents the drinking water standards of different agencies.

TABLE 1.5 Drinking Water Standards

Parameters	**BIS***	**ICMR**	**CPHEEO**	**WHO**
Colour, (Pt. units)	5	25	2	
Odour	Unobjectionable	Unobjectionable	Unobjectionable	Unobjectionable
Turbidity	5NTU	5NTU	2.5NTU	
*p*H	6.5 – 8.5	7 – 8.5	7 – 8.5	a
TDS, (mg/1)	500	500	500	a
Total hardness (as $CaCO_3$), (mg/1)	300	300	200	a
Ca(as Ca), (mg/1)	75	75	75	
Mg, (mg/1)	30	50	30	
Cl, (mg/1)	250	200	200	a
SO_4, (mg/1)	200	200	200	a
Fe, (mg/1)	0.3	0.1	0.1	a
Mn, (mg/1)	0.1	0.5	0.05	0.4(C)
Cu, (mg/1)	0.05	0.05	0.05	2.0
NO_3, (mg/1)	45	20	75	50
F, (mg/1)	1	1	1	1.5

(*Contd.*)

TABLE 1.5 (*Contd.*)

Parameters	BIS*	ICMR	CPHEEO	WHO
Phenolic compounds, (mg/1)	0.001	0.001	0.001	
Hg, (mg/1)	0.001	0.001	0.001	0.001
Cd, (mg/1)	0.01	–	0.01	0.003
Se, (mg/1)	0.01	–	0.01	0.01
As, (mg/1)	0.05	–	0.05	0.01(P)
Cn, (mg/1)	0.05	–	0.05	0.07
Pb, (mg/1)	0.05	–	0.1	0.1
Zn, (mg/1)	5	–	5	a
Anionic Detergents, (mg/1)	0.2	–	0.2	–
Cr, (mg/1)	0.05	–	0.05	0.05(P)
PAH, (μg/1)	–	–	0.2	
Mineral oil, (mg/1)	0.01	–	0.01	
Pesticides	Absent	–	–	
Aluminium, (mg/1)	0.03	–	–	
Alkalinity (as $CaCO_3$), (mg/1)	200	–	–	
Boron, (mg/1)	1	–	–	0.5(T)

BIS = Bureau of Indian Standards, ICMR = Indian Council of Medical Research,
CPHEEO = Central Public Health and Environmental Engineering Organisation, and
WHO = World Health Organisation
*IS 10500 : 1991
a = Not of health concern at levels found in drinking water. However, may affect the acceptability of drinking water; P = provisional guideline value, as there is evidence of a hazard, but available information on health effects is limited; T = provisional guideline value because calculated guideline value is below level that can be achieved through practical treatment methods; C = concentrations of substance at or below the health based guideline value may affect the appearance, taste or odour of water, leading to consumer complaints.

1.9.3 Quality Criteria for Irrigation Water

Whatever may be the source of irrigation water, viz, river, canal, tank, open well or tube well, some soluble salts are always dissolved in it. The nature and quantity of dissolved salts depend upon the source of water and its course before use. The main salts in water, from irrigation point of view, are calcium, magnesium, sodium and sometimes potassium, as cations, and chloride, sulphate, bicarbonate and carbonate, as anions. However, ions of some other elements, such as lithium, silicon, bromine, iodine, copper, nickel, cobalt, fluorine, boron, zirconium, titanium, vanadium, barium, rubidium, cesium, arsenic, antimony, bismuth, beryllium, chromium, manganese, lead, molybdenum, selenium and phosphorus, and organic matter, are present in minor quantities. These elements usually do not affect the quality of irrigation water as far as the total salt concentration is concerned, but some ions, such as selenium, molybdenum and fluoride, if absorbed by plants in excessive amounts, may prove harmful to animal life when taken by them through drinking water, feed or forage. Among the soluble constituents, calcium, magnesium, sodium, chloride, sulphate, bicarbonate, and boron are of prime importance in determining the quality of irrigation water and its suitability for irrigation. However, other factors, such as texture and structure of the soil, its drainage characteristic, nature of the crop grown and climatological condition, are equally important in determining the suitability of irrigation water.

The suitability of a water for irrigation will be determined by the amount and kind of salts present. With poor water quality, various soil and cropping problems can be expected to develop. Special management practices may then be required to maintain full crop productivity.

The following are the most common problems that result from using poor quality irrigation water:

Salinity

A salinity problem related to water quality occurs if the total quantity of salts in the irrigation water is high enough for the salts to accumulate in the crop root zone to the extent that yields are affected. If excessive quantities of soluble salts accumulate in the root zone, the crop has difficulty in extracting enough water from the salty soil solutions. Reduced water uptake by the plant usually results in slow or reduced growth.

Permeability

A permeability problem related to water quality occurs when the rate of water infiltration into the soil and its movement through the soil are reduced by the effect of specific salts in water, to such an extent that the crop is not adequately supplied with water and its yield is reduced. Poor soil permeability makes it more difficult to supply the crop with water. It may add to cropping difficulties through crusting of seedbeds, waterlogging of surface soil and accompanying disease, salinity, weed, oxygen and nutritional problems.

Toxicity

A toxicity problem occurs when certain constituents in the water are taken up by the crop and accumulate in amounts that result in reduced yield. This is usually related to one or more specific ions in the water, namely, boron, chloride and sodium.

Miscellaneous

Various other problems related to irrigation water quality occur with sufficient frequency and should be specifically noted. These include excessive vegetative growth, lodging and delayed crop maturity resulting from excessive nitrogen in the water supply, white deposits on fruits or leaves due to sprinkler irrigation with high bicarbonate water, and abnormalities indicated by an unusual *p*H of the irrigation water.

1.9.4 Water Quality Criteria

Of the several factors influencing irrigation water quality, the generally accepted criteria for judging quality are: (i) total salt concentration, as measured by electrical conductivity, (ii) relative proportion of cations, as expressed by sodium adsorption ratio (SAR), and (iii) bicarbonate and boron contents.

The suitability of irrigation water (SIW) can be expressed as

$$\text{SIW} = f\,(Q\ S\ P\ C\ D)$$

in which,

Q = quality of irrigation water
S = soil type
P = salt tolerance characteristics of the plant
C = climate
D = drainage characteristics of the soil

Some other factors, like the depth of water table, presence of a hard pan of lime or clay, calcium carbonate content in the soil, and potassium and nitrate ions in irrigation water, also indirectly affect the suitability of irrigation water. This is probably the main reason for the several classifications, varying in limits of salinity and other chemical indices. The soil type, major crops of the area, climate, and drainage characteristics profoundly influence the suitability of a particular water for irrigation. A highly saline water may be suitable in a well-drained, light textured, fertile soil, while a much less saline water may be more harmful for the same crop grown on a heavy textured soil with impeded drainage. It is the actual salt concentration near the root zone which determines the suitability of an irrigation water, rather than the chemical properties of irrigation water alone.

The quality of irrigation water is generally judged by its total salt concentration, relative proportion of cations or sodium adsorption ratio, and the contents of bicarbonate and boron.

Salinity. Irrespective of the ionic composition, the harmful effects of an irrigation water increases with its total salt concentration as it increases soil salinity significantly. Water of low salinity ($EC < 3$ dS/m) are generally composed of higher proportions of calcium, magnesium and bicarbonate ions. Highly saline water ($EC > 10$ dS/m) consist mostly of sodium and chloride ions. Moderately saline ($EC = 3$ to 9 dS/m) water has varying ionic compositions. Water containing high concentrations of sodium, bicarbonate and carbonate ions have high pH.

Sodium adsorption ratio (SAR). Any increase in the SAR of irrigation water increases the SAR of the soil solution. This ultimately increases the exchangeable sodium of the soil. Generally, there is a linear relationship between SAR and exchangeable sodium percentage (ESP) of the soil upto moderate ESP levels. At high ESP levels the relationship tends to be curvilinear.

In judging the suitability of irrigation water, both salinity and SAR should be kept in view along with the salinity and sodicity developed during the cropping period. Salinity increases the osmotic stress while adsorption of sodium is increased both by salinity and SAR.

Magnesium calcium ratio. At the same level of salinity and SAR, but with varying proportions of calcium and magnesium, adsorption of sodium by soils and clay minerals is more at higher Mg:Ca ratios. This is because the bonding energy of magnesium is generally less than that of calcium, allowing more sodium adsorption. It suggests that soil sodicity would increase at the same SAR if the water contains a higher proportion of magnesium to calcium. Thus, it is desirable to analyse both calcium and magnesium in irrigation water separately in order to predict the soil sodicity hazard more accurately. It is more important if the Mg:Ca ratio in irrigation water happens to be more than 4.

Bicarbonate. Irrigation water rich in bicarbonate content tend to precipitate soluble calcium and magnesium in the soil as insoluble carbonates:

$$2HCO_3 + Ca^{++} \rightleftharpoons CaCO_3 \downarrow + H_2O + CO_2 \uparrow$$

This leaves a higher proportion of sodium to divalent cations in the soil solution and increases the SAR. This bicarbonate-induced increase in the SAR of the soil solution ultimately results in higher adsorption of sodium on the soil exchange complex. Residual sodium carbonate (RSC) is used to assess the sodicity of carbonate and bicarbonate rich waters.

Boron. Though boron is an essential nutrient for plant growth, it becomes toxic beyond 2 ppm in irrigation water, for most field crops. It does not affect the physical and chemical properties of the soil but, at high concentrations, it affects the metabolic activities of the plant.

Potassium and nitrate. Potassium and nitrate ions are often present in significant amounts in irrigation water. Being essential nutrients, they act favourably in reducing the harmful effect of saline water on crop growth by providing these nutrients regularly, rather than by reducing soil salinity. Among these, the effect of the nitrate ion has been found more spectacular than potassium because irrigated soils are themselves deficient in nitrogen status and are generally well supplied with potassium. Regular supply of nitrate helps in mitigating the salt-induced nitrogen deficiency and increasing crop productivity.

1.9.5 Classification of Irrigation Water

Several classifications of irrigation water have been proposed in India and abroad, on the basis of their chemical characteristics and effect on crop growth. Amongst these, the classification proposed by the United States Soil Salinity Laboratory (USSSL) staff is widely used because it includes both the factors of salinity and sodium hazard (Richards, 1954). However, such a system is not very suitable under Indian conditions as water of greater salinity levels than the highest limit proposed by the USSSL staff are being successfully used in some areas of Haryana and Rajasthan.

Based on extensive research in different argo-ecological regions of India, Central Soil Salinity Research Institute (CSSRI), Karnal (Minhas and Samra, 2003) proposed the classification of ground water for irrigation into different groups and sub-groups as given in Table 1.6. Since each sub-group needs specific treatment and practices, this classification also serves the purpose of planning their development and management at micro level.

TABLE 1.6 Grouping of Ground Waters for Irrigation in India

Water quality class		ECiw	SAR	RSC
Main	**Sub-class**	**(dS/m)**	**(mmol/l)**	**(meq/l)**
Good		< 2	< 10	< 2.5
Saline	Marginally saline	2 – 4	< 10	< 2.5
	Saline	> 4	< 10	< 2.5
	High-SAR saline	> 4	> 10	< 2.5
Alkali	Marginally alkali	< 4	< 10	2.5 – 4.0
	Alkali	< 4	< 10	> 4.0
	Highly alkali	Variable	> 10	> 4.0

ECiw = Electrical conductivity of irrigation water; SAR = Sodium adsorption ratio, RSC = Residual sodium carbonate

Source: Minhas & Samra (2003)

1.9.6 Water Quality Guidelines for Irrigation

The suitability of specific water for irrigation depends on soil, climate, crop etc. and the other management practices followed. Therefore, broad guidelines for assessing the suitability of irrigation waters have been suggested by Central Soil Salinity Research Institute (CSSRI), Karnal (Table 1.6). The recommended guidelines for utilizing poor quality water for their wide applicability in different agro-ecological zones of India are given in Table 1.7 (Gupta, 1998). For meeting site specific water quality objectives, factors like water quality parameters, soil texture, crop tolerance and rainfall have been given due considerations. Some of the suggestions added to these guidelines include use of gypsum for saline water having SAR > 20 and Mg:Ca > 3 and rich in silica; fallowing during rainy season when SAR>20 and higher salinity waters are used in low rainfall areas; additional phosphorus application especially when Cl: SO_4 ratio is > 2.0; canal water preferably at early growth stages including pre-sowing irrigation for conjuctive use with saline water; putting 20 per cent extra seed rate and quick post-sowing irrigation (within 2 – 3 days) for better germination; when EC_{iw} (Electrical conductivity of irrigation water) < EC_e (Electrical conductivity of saturation extract) (0 – 45 cm Soil at harvest of rabi crops), saline water irrigation just before the onset of monsoon; use of organic material etc. For soils having (i) shallow water table (within 1.5 m in *kharif*) and (ii) hard sub soil layers, the next lower EC_{iw}/alternate modes of irrigation (canal/saline) is applicable.

TABLE 1.7 Guidelines for using Saline Irrigation Waters in India

Soil texture (% clay)	**Crop tolerance**	**EC_{iw} (dS/m) limit for rainfall region**		
		< 350	**350 – 550**	**> 550 mm**
a. Saline water (RSC < 2.5 meq/litre)				
Fine	Sensitive	1.0	1.0	1.5
(> 30)	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine	Sensitive	1.5	2.0	2.5
(20-30)	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse	Sensitive	2.0	2.5	3.0
(10-20)	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse	Sensitive	~	3.0	3.0
(< 10)	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

b. Alkali water (RSC > 2.5 meq/litre, EC_{iw} < 4.0 dS/m)

Soil texture (% clay)	**SAR $(mmol/litre)^{1/2}$**	**Upper limit of RSC**	**Remarks**
Fine (> 30)	10	2.5 – 3.5	Limits pertain to *kharif* fallow/*Rabi* crop rotation when annual rainfall is 350–550 mm. When waters have Na < 75% (Ca + Mg > 25%) or rainfall is > 550 mm, the
Moderately fine (20 – 30)	10	3.5 – 5.0	upper limit of RSC range becomes safe. For double cropping, RSC neutralization with gypsum is essential based on quantity of water used during the *rabi* season.
Moderately coarse (10 – 20)	15	5.0 – 7.5	Grow low water requiring crops during *kharif*.
Coarse (< 10)	20	7.5 – 10.0	Avoid rice.

1.10 TYPES OF WATER WELLS

Diverse geological formations require different types of wells for tapping ground water for irrigation and water supply. The choice of the type of well for irrigation is influenced by the size of farm holdings and the relative preference given to private, cooperative and public wells. Broadly, water wells may be divided into three categories, namely, dug wells, dug-cum-bore wells, and tube wells. Tube wells may be deep or shallow.

1.10.1 Dug Wells

Dug wells comprise of open surface wells of varying dimensions dug or sunk from the ground surface into the water-bearing stratum. They may be circular or rectangular in cross-section. Usually, two types of wells are constructed: masonry (lined) wells and unlined wells in the hard rock. A typical masonry well, usually constructed in alluvial or semi-consolidated formations, has a masonry steining wall sunk in sub-soil by applying static weight with sand bags and simultaneously scooping out earth from inside. A typical dug well constructed in a hard-rock formation is usually an open excavated pit through the top soil and weathered rock. The top portion along the soil mantle is usually lined with bricks or stones. The well taps water from the sides as well as from the bottom, and is generally large to provide for storage of water.

1.10.2 Dug-cum-Bore Wells

Dug wells are frequently bored through the bottom to augment their yield. These are referred to as dug-cum-bore wells.

In sedimentary formations, boring consists essentially of drilling a small bore of diameter usually ranging from 7.5 cm to 15 cm, through the bottom of the well, and extending the bore down to a layer of good water-bearing formation to tap that aquifer. Bores are made by percussion or calyx rigs or down-the-hole rigs.

1.10.3 Tube Wells

A tube well consists essentially of a bore hole drilled into the ground for tapping ground water from the pervious zone. Tube wells constructed in India may be broadly divided into three categories: (i) shallow tube wells; (ii) deep tube wells; and (iii) bore wells.

Shallow Tube Wells

A tube well in a sedimentary formation, not exceeding 60 to 70 m in depth, is called a shallow tube well. They are lined with pipes usually made of mild steel, rigid PVC or other types of pipes. Shallow tube wells are usually privately owned by individual farmers.

Deep Tube Wells

Deep tube wells usually extend to depths of 100 m or more and are designed to give a discharge of 100 to 200 m^3/h. These are usually drilled by direct rotary or reverse circulation rigs, except in boulder formations where percussion or rotary-cum-percussion rigs have to be used. They operate round the clock during the irrigation season. Usually, deep tube wells in India are constructed as artificially gravel packed wells. Slotted steel tubes are mainly used as screens and it has hitherto not been possible to cut satisfactory slots of width less than 1.6 mm on these tubes. Deep tube wells in India are usually owned by the Government or public sector organizations like state tube well corporations.

Bore Wells

Tube wells in hard rock areas are called bore wells because the bore hole is able to hold on its own in the bottom portion and a tube is pushed only in the upper weathered zone. These wells usually depend on joints, fissures and fractures in rock formations for their water supply. Even with a heavy drawdown of 20 to 30 m, such wells are usually not able to yield more than 5 to 10 m^3/h, except when they tap some embedded water bearing strata.

1.11 GROUND WATER RESOURCE ASSESSMENT

Ground water is replenishable resource, the quantification of which is of paramount importance for drawing plans for its utilization, management and conservation. Excessive ground water development during recent years had shown that the resource is not inexhaustible as is evidenced by the continuous water level decline in some parts of the country. Although the situation is not alarming, the need for an appraisal of ground water resource is apparent. Since 1970 AD, extensive availability of credit facilities, through the National Bank for Agriculture and Rural Development (NABARD) and Commercial and Land Development Banks for well sinking programmes and installation of pump sets and energization by the Rural Electrification Corporation, has given an impetus to ground water development. Rapid industrialization and rural and urban water supply programmes have also given rise to heavy withdrawal of ground water in localized areas. Even in areas where there is surface water irrigation under the various major, medium and minor irrigation projects, ground water is playing in increasingly important role in supplementing the irrigation water by conjunctive use of ground water with surface water.

A significant breakthrough in ground water development came around the year 1965 with the development of high yielding varieties of crops. It was realized that ground water development was essential for providing controlled and assured supply of water needed for irrigation of these crops. It is well recognized that ground water is an important and assured source of water than surface water sources which are affected seriously during periods of drought and erratic rainfall. The ground water resources are dynamic in nature, as they grow with the expansion of canal irrigation.

1.11.1 Poor Quality Ground Water Resources

No systematic attempts have been made so far in the country to arrive at the estimates of saline ground water resources. Gupta *et al* (1994) prepared a map of ground water quality for irrigation, which has been the first approximation in the country (Fig. 1.11). Four legends have been used in mapping the ground water quality. These are good water ($EC_i < 2$ dS/m and SAR < 10), saline water ($EC_i > 2$ dS/m and SAR < 10), high SAR saline water ($EC_i > 4$ dS/m and SAR > 10) and alkali water ($EC_i << 4$ dS/m, SAR < 10 and RSC > 2.5).

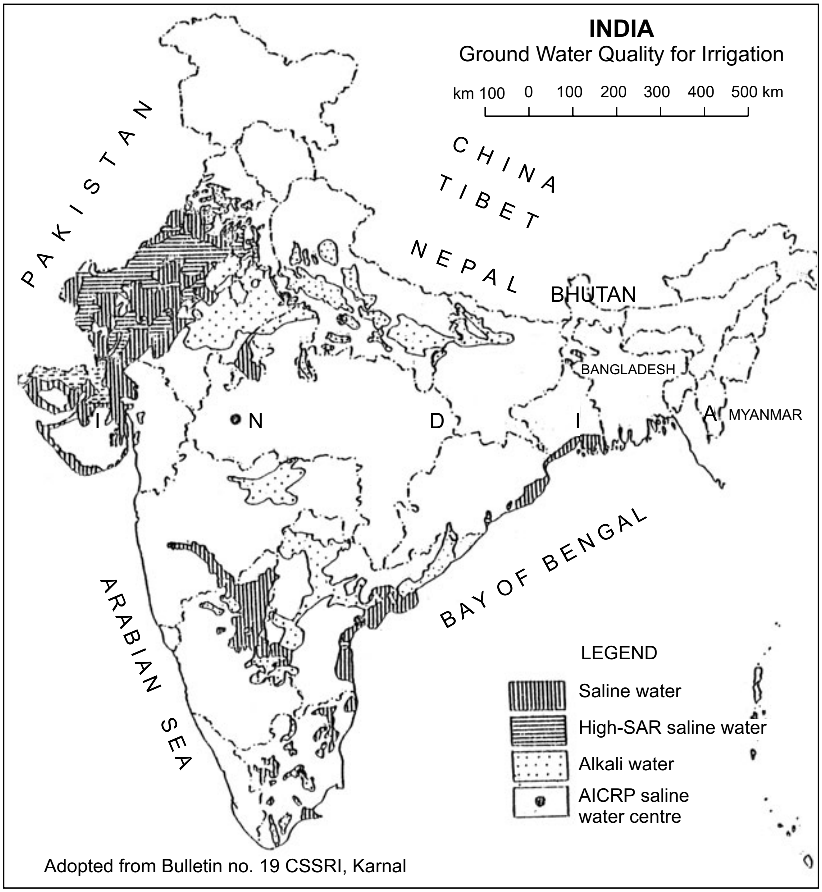

Fig. 1.11 Ground water quality for irrigation (First Approximation)
Source: Gupta *et al.* (1994)

Ground water surveys have shown that about 41 to 84 per cent of the well waters in the north west states of India are brackish. Vertical as well as lateral variation in ground water quality are encountered even at short distances. Higher salinity ground waters are mostly encountered in arid parts of north-west states like Rajasthan, Gujarat and Haryana (Minhas & Tyagi, 1998). The Central Ground Water Board approximated that the total area underlain with saline ground water in India (EC > 4 dS/m) is 19.34 m ha (GWREC, 1997).

1.12 STATUS OF GROUND WATER DEVELOPMENT IN INDIA

In India, the use of ground water through dug wells may be traced back to pre-historic times. The first large-scale venture in scientific planning and development of ground water was undertaken in India in 1934 when a project for the construction of about 1500 tube wells in the Indo-Gangetic basin in Uttar Pradesh was initiated. The rapid stride in ground water use for irrigation in India commenced in the beginning of Five Years Plans in 1951. The growth has, however, been so phenomenal that, of the total ground water draft, about 90 per cent is accounted for by irrigation alone.

There has been large scale increase in the growth of ground water abstraction structure. During the period 1951–97, the number of dug wells increased from 3.86 million to 10.12 million, that of shallow tube wells from 3.00 to 5.38 million and public tube wells from negligible to 68000. The number of electric pump sets has increased from negligible to 9.34 million and the diesel pump sets from 6000 to 4.59 million. During the period 1951 to 1997 the ground water based irrigation potential steadily increased from 6.5 million hectares to 41.99 million hectares. The ultimate irrigation potential from ground water is estimated as 64 million hectares.

The estimated annual replenishable ground water potential of India is about 43.2 million ha-m, keeping a provision of 7.1 million ha-m of ground water for drinking, industrial and other uses, 36.1 million ha-m is available for irrigation. Besides this, about 1081.2 million ha-m of ground water is available as static ground water resource below the zone of water level fluctuation (Sharma, 2001). The National Water Policy forbids the utilization of this static reserve. The net draft in 1998 was 13.5 million ha-m. The stage of ground water development in various States and Union Territories of India is shown in Table 1.8. There is a wide scale variations in stage of ground water development among states. In Punjab, 99 per cent of the annual replenishable recharge available for irrigation has been tapped. The other states, where percentage of development is more than 50 per cent are Haryana (75 per cent) and Rajasthan (73 per cent). The states with level of development less than 10 per cent are Goa (8.3 per cent), Assam (7.5 per cent), Chattisgarh (5.6 per cent) and Jammu & Kashmir (1.1 per cent). The average stage of ground water development at national level is 37.2 per cent.

Inspite of national scenario on availability of ground water favourable, there are certain areas in country facing the serious problem of declining water table because of over exploitation of ground water resources. Decline in water table of more than 4 m has been observed during the last twenty years in many states of India. A list of district in different States of India with decline of more than 4 m has been recorded during the period 1982 to 2001 is given in Table 1.9. The decline in water table can be checked by adopting suitable technologies to reduce ground water draft and increase ground water recharge.

1.13 ARTIFICIAL RECHARGE OF GROUND WATER

Artificial recharge is the process by which the ground water reservoir is augmented at a rate exceeding that under natural conditions of replenishment. Any man-made scheme or facility that adds water to an aquifer may be considered to be an artificial recharge system. The basic purpose of artificial ground water recharge is to replenish the ground water to check decline in water table, conserve water for future use, control of salt-water encroachments etc. Most commonly used artificial recharge methods can be classified as (a) direct, (b) indirect, and (c) combination. The various artificial recharge techniques commonly used under these groups are shown in Table 1.10 (CGWB, 1994).

1.13.1 Direct Method

The direct methods include surface spreading, sub-surface techniques and combination of surface and sub-surface techniques.

TABLE 1.8 Ground Water Resource of India (as on 01.04.98)

Sl. no.	States	Total replenishable ground water resource Mha-m/yr	Provision for domestic industrial & other uses Mha-m/yr	Available ground water resource for irrigation in net terms Mha-m/yr	Utilizable ground water resource for irrigation in net terms Mha-m/yr	Gross draft estimated on prorata basis Mha-m/yr	Net draft Mha-m/yr	Balance ground water resource for future use in net terms	Level of ground water development (%)
1	Andhra Pradesh	3.52909	0.52936	2.99973	2.69975	1.11863	0.78304	2.21668	26.10
2	Arunachal Pradesh	0.14385	0.02158	0.12227	0.11005	–	–	0.12227	–
3	Assam	2.24786	0.33718	1.91068	1.71962	0.20356	0.14249	1.76819	7.46
4	Bihar	2.69796	0.40471	2.29326	2.06394	1.17895	0.82527	1.46800	35.99
5	Chattisgarh	1.60705	0.24106	1.36599	1.22939	0.10925	0.07647	1.28952	5.60
6	Goa	0.02182	0.00327	0.01855	0.01669	0.00219	0.00154	0.01701	8.30
7	Gujarat	2.03767	0.30566	1.73199	1.55881	1.21895	0.85327	0.87872	49.27
8	Haryana	1.11794	0.16769	0.95025	0.85523	1.02637	0.71846	0.23179	75.61
9	Himachal Pradesh	0.02926	0.00439	0.02487	0.02238	0.00591	0.00413	0.02073	16.63
10	Jammu and Kashmir	0.44257	0.06640	0.37620	0.33860	0.00586	0.00403	0.37217	1.07
11	Jharkhand	0.66045	0.09907	0.56138	0.50525	0.17352	0.12146	0.43992	21.64
12	Karnataka	1.61750	0.24186	1.37564	1.23665	0.64973	0.45481	0.92083	33.06
13	Kerala	0.79003	0.13135	0.65869	0.59281	0.17887	0.12509	0.53360	18.99
14	Madhya Pradesh	3.48186	0.52228	2.95958	2.66362	1.05494	0.73846	2.22112	24.95
15	Maharashtra	3.78677	1.23973	2.54704	2.29233	1.26243	0.88370	1.66334	34.70
16	Manipur	0.31540	0.04730	0.26810	0.24129	Neg.	Neg.	0.26810	Neg.
17	Meghalaya	0.05397	0.00810	0.04587	0.04128	0.00260	0.00182	0.04405	Neg.
18	Mizoram				Not assessed				
19	Nagaland	0.07240	0.01090	0.06150	0.05535	Neg.	Neg.	0.06150	Neg.
20	Orissa	2.01287	0.30193	1.71094	1.53984	0.37196	0.26037	1.45057	15.22
21	Punjab	1.81923	0.18192	1.63730	1.47357	2.30028	1.61020	0.02710	98.34
22	Rajasthan	1.26021	0.19977	1.06044	0.95440	1.10350	0.77245	0.28799	72.84
23	Sikkim				Not assessed				
24	Tamil Nadu	2.64069	0.39610	2.24458	2.02013	2.00569	1.40398	0.84060	62.55

(*Contd.*)

TABLE 1.8 (*Contd.*)

Sl. no.	States	Total replenishable ground water resource Mha-m/yr	Provision for domestic industrial & other uses Mha-m/yr	Available ground water resource for irrigation in net terms Mha-m/yr	Utilizable ground water resource for irrigation in net terms Mha-m/yr	Gross draft estimated on prorata basis Mha-m/yr	Net draft Mha-m/yr	Balance ground water resource for future use in net terms	Level of ground water development (%)
255	Tripura	0.06634	0.00995	0.05639	0.05075	0.02692	0.01885	0.03754	33.43
26	Uttar Pradesh	8.25459	1.23819	7.01640	6.31476	4.25171	2.97619	4.04021	42.42
27	Uttaranchal	0.28411	0.04262	0.24149	0.21734	0.09776	0.06843	0.17306	28.34
28	West Bengal	2.30914	0.34637	1.96277	1.76649	0.90250	0.63175	1.33102	32.19
	Total States	**43.30063**	**7.09873**	**36.20191**	**32.58033**	**19.25207**	**13.47627**	**22.72564**	**37.23**
	Union Territories								
1	Andaman & Nicobar				Not Assessed				
2	Chandigarh	0.00297	0.00044	0.00252	0.00227	0.00351	0.00245	0.00007	–
3	Dadar & Nagar	0.004							
22	0.00063 Haveli	0.00359	0.00323	0.00065	0.00046	0.00313	12.81		
4	Daman	0.00071	0.00011	0.00060	0.00054	0.00069	0.00048	0.00012	80.00
5	Diu	0.00037	0.00006	0.00031	0.00028	0.00042	0.00029	0.00002	94.84
6	NCT Delhi	0.02916	0.01939	0.00977	0.00879	0.01684	0.01180	–0.00203	120.78
7	Lakshdweep	0.03042	0.00456	0.00195	0.00176	0.00109	0.00076	0.00119	39.12
8	Pondicherry	0.01746	0.00262	0.01484	0.01335	0.01645	0.01152	0.00332	77.63
	Total UTs	**0.08530**	**0.02782**	**0.03358**	**0.03022**	**0.03966**	**0.02777**	**0.00581**	
	Grand Total	**43.38593**	**7.12655**	**36.25938**	**32.63345**	**19.29173**	**13.50404**	**22.73145**	**37.24**

Source: MOWR (2003)

TABLE 1.9 List of Districts in India with more than 4 m Fall in Water Table During 1982-2001 (Pre-monsoon Period)

State-wise Pockets with Fall in Water Table (Pre-Monsoon Period) in India (1982 to 2001)		
	Fall in water table	
States	**4–6 m**	**> 6 m**
Andhra Pradesh	Adilabad, Anantpur, Chittoor, Hyderabad, Karimnagar, Khammam, Kurnool, Mahbubnagar, Medak, Nalgondam, Nellore, Nizamabad, Prakasam, Ranga Reddy, Srikamulam, Warangal, Vijaynagaram, Visakhapatnam,	Adilabad, Anantapur, East Godavari, Hyderabad, Karimnagar, Kurnool, Mabhubnagar, Medak, Prakasam, Srikamulam, Vijaynagaram, Warangal, Visakhapatnam, W-Godavari
Bihar	Gaya, Giridih, Lohardaga, Palamu	–
Chhatisgarh	Baster, Bilaspur, Janjgir, Champa, Kanker	Baster, Dantewada, Durg, Raigarh
Gujarat	Ahmedabad, Amreli, Banaskantha, Baroda, Bharuch, Bhavnagar, Jamnagar, Junagadh, Kheda, Kutch, Mehsana, Rajkot, Sabarkantha, Surat, Surendranagar, Valsad	Ahmedabad, Amreli, Banaskantha, Baroda, Bharuch, Bhavnagar, Dangs, Jamnagar, Junagadh, Kheda, Kutch, Mehsana, Panchmahal, Rajkot, Sabarkantha, Surat, Surendranagar
Haryana	Faridabad, Gurgaon, Hissar, Jind, Kaithal, Karnal, Kurukshetra, Mahendragarh, Panchkula, Panipat, Rewari, Sirsa	Bhiwani, Faridabad, Fatehabad, Gurgaon, Kaithal, Kurukshetra, Mahendragarh, Panipat, Rewari, Rohtak, Sirsa, Yamunanagar
Delhi	South-West, South, New Delhi, North West, West, Central	South, South-West, New Delhi
Karnataka	Bangalore, Belgaum, Bidar, Bijapur, Dharwad, Gadag, Gulbarga, Kolar, Koppala, Shimoga, Tumkur, Uttar Kannada	Bangalore, Belary, Belgaum, Bidar, Bijapur, Chamarajanagara, Chitradurga, Davanagere, Gadag, Gulbarga, Hassan, Haveri, Mandya, Mysore, Raichur, Shimoga, Tumkur, Uttar Kannada
Kerala	Ernakulam, Idukki, Kannur, Kasaragod, Kolam, Kottayam, Kozhikode	Iddukki, Kannur, Kolam, Kottayam, Thiruvanathapuram
Madhya Pradesh	Betul, Bhind, Chhatarpur, Chhindwara, Damoh, Datia, Dewas, Dhar, Guna, Jabalpur, Katni, Khandwa, Khargone, Morena, Narsinghpur, Nimach, Panna, Raisen, Ratlam, Rewa, Sagar, Satna, Sehore, Shajapur, Sheopur, Shivpuri	Barwani, Betul, Bhind, Chatarpur, Datia, Dewas, Guna, Gwalior, Hoshangabad, Indore, Jabalpur, Khandwa, Khargone, Mandsaur, Morena, Narsinghpur, Nimach, Raisen, Rajgarh, Rewa, Shajapur, Vidisha
Maharashtra	Ahmednagar, Akola, Amravati, Aurangabad, Beed, Bhandara, Buldhana, Chandrapur, Dhule, Gadchiroli, Jalgaon, Jalna, Latur, Nagpur, Nanded, Nasik, Parbhani, Sangli, Satara, Sholapur, Thane, Wardha, Yavatmal	Ahmednagar, Akola, Amravati, Aurangabad, Beed, Bhandara, Chandrapur, Jalgaon, Kolhapur, Latur, Nanded, Pune, Sholapur

(*Contd.*)

TABLE 1.9 (*Contd.*)

State-wise Pockets with Fall in Water Table (Pre-Monsoon Period) in India (1982 to 2001)

States	Fall in water table 4–6 m	> 6 m
North Eastern States	Jorhat, Kamrup, Karbi-Anglong, South Tripura, West Tripura	Morigaon
Orissa	Balasore, Bolangir, Boudh, Cuttack, Deogarh, Dhenkanal, Gajapati, Ganjam, Kalahandi, Keonjhar, Khurda, Koraput, Mayurbanj, Nayagarh, Nowrangpur, Phulbani, Sambalpur, Suvarnpur	Angul, Balasore, Bolangir, Dhenkanal, Gajapati, Ganjam, Khurda, Koraput, Malkangiri, Phulbani, Sundergarh, Suvarnpur
Punjab	Amritsar, Bhatinda, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Patiala, Sangrur	Amritsar, Bhatinda, Ferozepur, Jalandhar, Ludhiana, Moga, Patiala, Ropar, Sangrur
Rajasthan	Ajmer, Alwar, Banswara, Baran, Barmer, Bundi, Chittorgarh, Churu, Dausa, Dungarpur, Hanumangarh, Jaipur, Jalore, Jhalawar, Jodhpur, Kota, Nagpur, Pali, Rajsamand, Sirohi, Tonk, Udaipur	Ajmer, Alwar, Banswara, Baran, Barmer, Bhilwara, Bikaner, Bundi, Chittorgarh, Churu, Dholpur, Dungarpur, Jaipur, Jalore, Jhalawar, Jhunjhunu, Jodhpur, Kota, Pali, Rajsamand, Sawai Madhopur, Sikar, Sirohi, Tonk, Udaipur
Tamil Nadu	Coimbatore, Dharmapuri, Dindigul, Kancheepuram, Chennai, Theni, Tiruvannamalai, Tuticorin	Coimbatore, Cuddalore, Dharmpauri, Erode, Kanyakumari, Namakkal, Perambalur, Pudukkottal, Sivaganga, Tanjavur, Tirunelveli, Tiruvallur, Tiruvarur
Uttar Pradesh	Agra, Aligarh, Allahabad, Badaun, Ballia, Barabanki, Bareilly, Bijnor, Bulandsahar, Etah, Etawah, Faizabad, Fatehgarh, Fetehpur, Ghaziabad, Hamirpur, Hordoi, Jalaun, Jaunpur, Jhansi, Kanpur, Lakhimpur, Lalitpur, Lucknow, Mainpuri, Mathura, Mirzapur, Moradabad, Muzaffarnagar, Pratapgarh, Raebareli, Rampur, Saharanpur, Shahjahanpur, Sitapur, Sultanpur, Unnao	Agra, Aligarh, Allahabad, Badaun, Banda, Barabanki, Bareilly, Bulandsahar, Deoria, Etah, Etawah, Fatehgarh, Fatehpur, Hamirpur, Hardoi, Jaunpur, Jhansi, Kanpur, Lucknow, Mainpuri, Mathura, Meerut, Moradabad, Muzaffarnagar, Pratapgarh, Raebareli, Sultanpur, Unnao
West Bengal	Bankura, Birbhum, Koochbihar, Purulia	Bankura, Bardhman, Birbhum, Dakshin Dinajpur, Jalpaiguri, Purulia

Source: Lok Sabha Unstarred Question No. 3052, dated 09.12.2002.

Surface Spreading Techniques

Ground water recharge by surface spreading method means infiltration of water from surface of the soil through the vadoze zone to the saturated part of the aquifer. The downward movement of water is governed by a number of factors such as vertical permeability of the vadoze zone, presence or absence of limiting layers having, low vertical permeability and influence of physical, chemical and bacteriological processes. The requirement of successful recharge through spreading method are: (i) sufficiently thick permeable unconfined aquifer; (ii) permeable surface soil to maintain high infiltration rate;

(iii) permeable vadoze zone free from clay lenses; (iv) sufficiently deep ground water level to accommodate the water table rise without causing waterlogging; (v) moderate hydraulic conductivity of aquifer material; and (vi) gently slopping land without gullies or ridges.

Surface water spreading techniques can be broadly classified as (i) flooding; (ii) ditch and furrow method; (iii) recharge basins; (iv) percolation tanks; (v) stream modification; (vi) conservation of water resources in agriculture field; and (viii) soil and water conservation works.

TABLE 1.10 Artificial Recharge Methods

ARTIFICIAL RECHARGE METHODS

Direct methods		Indirect methods		
Surface spreading techniques	Sub-surface techniques	Induced recharge	Aquifer modification	Ground water conservation structures
1. Flooding	1. Injection wells	1. Pumping wells	1. Bore blasting	1. Ground water Dams/Under ground *bandharas*
2. Ditch and furrows	2. Gravity head recharge wells	2. Collector wells	2. Hydro-fracturing	2. Fracture sealing cementation technique (F.S.C.)
3. Recharge basin	3. Connector wells	3. Infiltration galleries		
4. Runoff conservation structures (I) Gully plugs (II) Bench terracing (III) Contour bund (IV) *Nala* bund (V) Percolation tank	4. Recharge pits			
5. Stream modification	5. Recharge shafts			
6. Surface irrigation				

Flooding. This method is the least costly of all water spreading methods. In this method, the surplus water from the canal or stream is diverted to the adjoining areas through a delivery canal. Embankments are made on two sides of the area to ensure proper contact time and water spread, as well as to put back the unutilized surface water to the canal/stream downstream side. In addition to the requirements for spreading method, described above, the specific requirements of this technique is the availability of sufficiently large area adjacent to the canal/stream, which is normally not used for any other purpose and can be legally acquired.

Ditch and furrow method. This system is used only in case of irregular topography, where flooding is not possible. The water from stream is diverted to the ditches through delivery canal/supply ditch to a net work of ditches spread in the area. Excess water from the ditches is diverted back to the canal/stream.

Recharge basin. The basins used for artificial ground water recharge are either excavated or enclosed by dykes or levees (Fig. 1.12). They are commonly built parallel to streams or at other locations to which the water can be diverted from the recharge source. In alluvial areas, multiple recharge basins are generally constructed. This system has number of advantages such as efficient use of space and reduction in suspended matter when water flows from upstream basin to downstream basin. The specific characteristics and design guidelines are as under:

(i) The bottom of individual basins should be sufficiently wide to permit movement of scrapers for desilting operation,
(ii) The inlet and outlet of the basin should be diagonally opposite to permit adequate water circulations in individual basin,
(iii) Water released to the basin should have minimum sediment,
(iv) The infiltration capacity can be improved by alternate loading and unloading, periodic scraping of top surface layer etc.,
(v) The design of the basin may be based on actual infiltration studies.

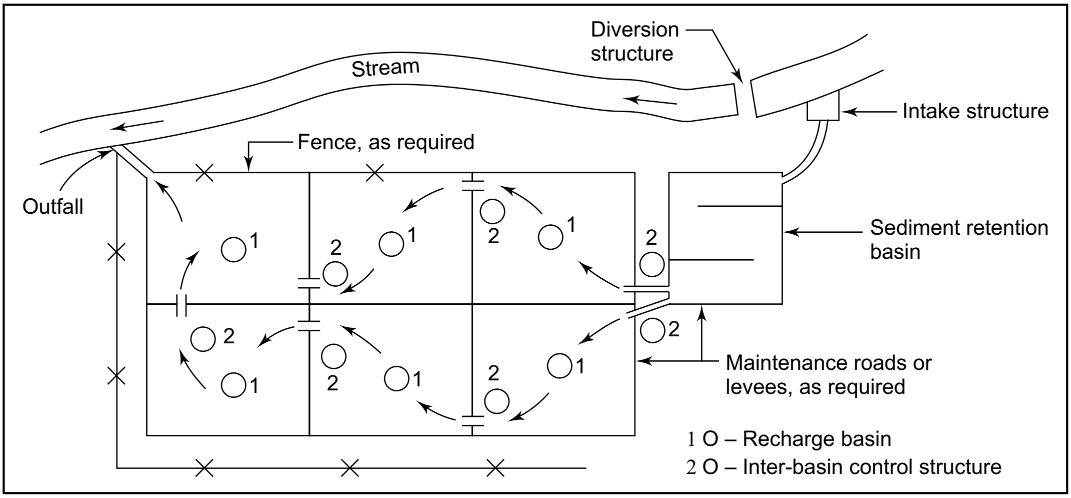

Fig. 1.12 Schematic sketch showing the layout of recharge basins

Percolation tanks. Percolation tanks are small water harvesting structures created by making low elevation stop dams across streams or located adjacent to a stream by excavation and connected to the stream by delivery canal. The requirements of successful recharge operation through percolation tanks are:

(i) High permeability of rocks coming under submerged areas,
(ii) Uniform degree and extent of weathering of rocks,
(iii) Sufficient rainfall ensuring filling of percolation tank every year,
(iv) Light sandy soils in catchment area to avoid silting up of tank bed,
(v) The size of catchment may vary from 2.5 to 8 sq. km,
(vi) Existence of good phreatic aquifer with lateral continuity upto percolation tank,
(vii) Adequate number of ground water structures in the benefited zone of percolation tanks to fully utilize the additional recharge.

Stream modification. The recharge through the natural streams/drains can be increased by determining the stream flow and stream bed area in contact with water. The methods used include provision of low head check dams allowing flood flows passing over them (Khepar *et al*. 2000a), and construction of L-shaped levees in the stream bed allowing the passage of flow in a zig zag manner, before the start of rainy season. This method has been successfully used in alluvial areas, but also can be used in hard rock areas in case of weathered rocks.

Conservation of water resources in agriculture fields. The declining water table can be controlled either by reducing the ground water draft and/or increasing the ground water recharge. Both these objectives are achieved by conservation of rainfall and/or surplus canal water during rainy season in paddy/sugarcane fields. The water conserved in the field meet partial requirement of irrigation and thus decreases the ground water draft as well as increases the ground water recharge. The studies carried out at Punjab Agricultural University (Khepar *et al*. 2000b) have revealed that in case of paddy fields an effective dike height of 15.0, 17.5 and 20 cm under light, medium and heavy soils respectively are useful to conserve more than 95 per cent of the rainfall during the rainy season.

The run off conservation structures such as check dams, gully plugs, bench terracing, contour bund, improved agronomic practices etc. induce more infiltration and enhance ground water recharge. These works act like water spreading measures to recharge ground water.

Sub-surface Techniques

The sub-surface techniques are used to recharge the confined aquifer, as the same cannot be recharged by infiltration from soil surface due to the intervening impervious layers lying between the unconfined and confined aquifer. Commonly adopted sub-surface techniques include: (i) injection wells; (ii) gravity head recharge wells; (iii) connector wells; (iv) recharge pits; and (v) recharge shaft.

Injection wells. Injection wells are tube wells in which the treated surface water is pumped in for recharging the confined aquifer (Fig. 1.13). This technique is advantageous when there is a limitation of space as in urban area and also in coastal regions to arrest the ingress of sea water. Their construction is similar to gravel packed pumping wells tapping a single or multiple aquifers. The only difference is that the upper section of the well is plugged with cement to prevent leakage of pressure from annular space of borehole and well assembly. The injection wells get clogged. To prevent the clogging, the recharge water should be properly treated for removal of suspended material and harmful bacterias. The quality of surface water to be recharged should satisfy the criteria laid down for drinking water. Periodic re-development is required to maintain the recharge rate.

The recharge well can be used as recharge-cum-pumping well. It should be designed to fully penetrate the aquifer to avoid additional head loss due to partial penetration.

Gravity head recharge wells. Ground water can be recharged by directing the surface water to bore wells, tube wells and dug wells. The aquifer is recharged under gravity head. The recharge head available is the elevation difference between the surface water level in feeder reservoir and elevation of water table or piezometric head. The recharge rate is obviously much less as compared to recharge through injection wells. The abandoned wells, which were giving good yield, prove more suitable for ground water recharge as compared to poor yielding wells. Only properly filtered and disinfected water should be used for recharge. The water should be diverted to the well through a conductor pipe to avoid impact waves, air locking etc.

Connector wells. Connector wells are used for ground water recharge from one aquifer to another. The aquifers having higher heads start recharging aquifers having lower heads. Usually deeper aquifers are recharged from phreatic aquifer. Thus connector well connects all the aquifer zones encountered while boring.

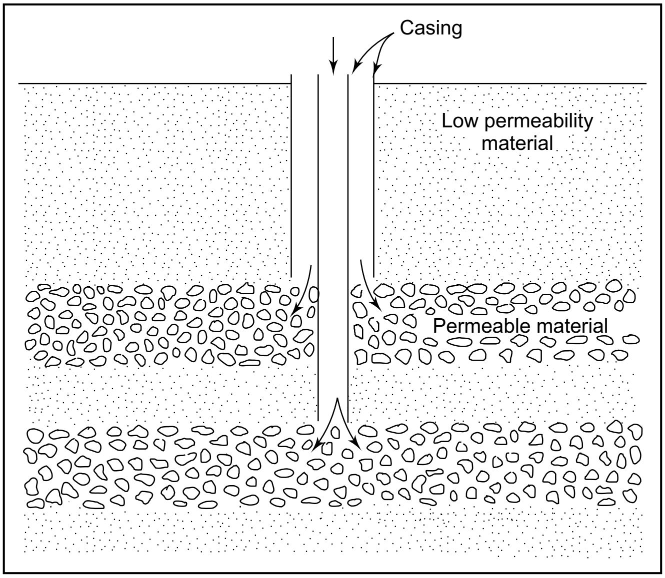

Fig. 1.13 Injection well technique
Source: CGWB, 1994

Recharge pits. The recharge pits are used for ground water recharge when the phreatic aquifers are not hydraulically connected with surface water due to the presence of impermeable low/permeable layers or lenses, which restricts the infiltration of surface water into the aquifer. The recharge pits (Fig. 1.14) recharge through the vadoze zone and may not necessarily penetrate or reach the unconfined aquifer as required in case of gravity head recharge well. The water used for recharge should be as silt free as possible. It will be desirable to provide a thin layer of filter at the bottom of the pit to avoid clogging of permeable strata.

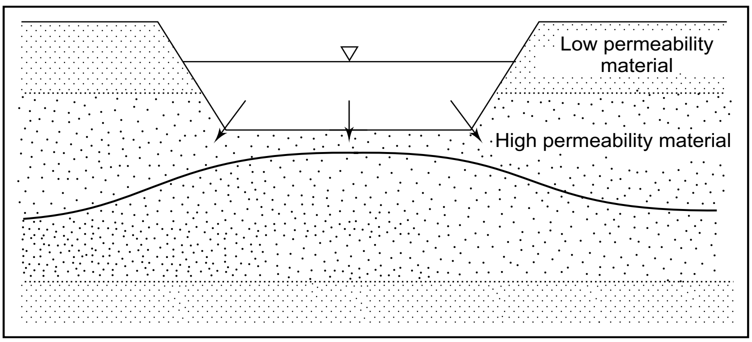

Fig. 1.14 Sectional view of a recharge pit

Recharge shaft. The recharge shaft is similar to recharge pit but smaller in diameter (Fig. 1.15). It is suitable when the water table aquifer is overlain by poorly permeable strata. In case of shallow depth and non-caving type strata, the recharge shafts can be excavated manually, while for greater depth it can be drilled by reverse/direct rotary drilling rig. The diameter may vary from 0.8 m (drilled shaft) to about 2.0 m (manually excavated). The difference between a recharge well and shaft is that the shaft ends in more pervious strata below confining layer, without touching the water table, while the recharge wells penetrates the entire confined aquifer. The shallow shafts are backfilled by inverted filter comprising boulders and top few metres by gravel and sand filter. The deeper shafts are lined and not necessarily completely backfilled. Only a few metres at the bottom may be filled with gravel followed by sand filter.

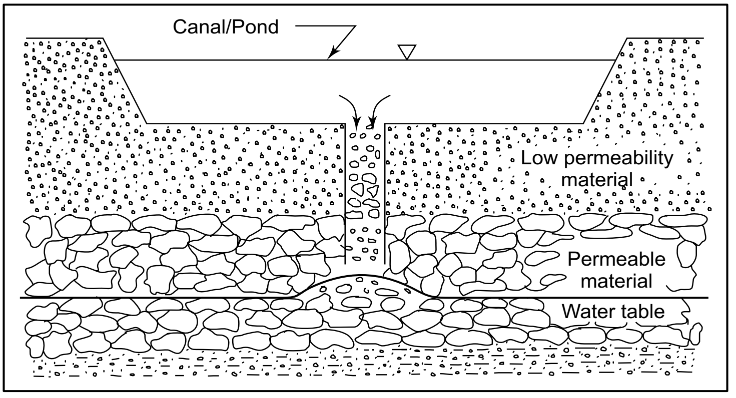

Fig. 1.15 Sectional view of a ground water recharge shaft at the bottom of a canal/pond, partially penetrating the permeable material underneath

1.13.2 Indirect Methods

The indirect methods include (i) induced recharge; (ii) aquifer modification; and (iii) ground water conservation techniques.

Induced recharge. The artificial recharge from surface water, hydraulically connected with aquifer can be induced by pumping ground water through wells, collector wells and infiltration galleries, the choice of which depends upon the geohydrological condition of the area.

Aquifer modification. The aquifer modification technique such as bore well blasting and hydrofracturing modify the aquifer characteristic enhancing its capacity for ground water recharge. Thus these techniques are also artificial yield augmentation measures, rather than artificial recharge measures. Moreover, these techniques are not only used to increase the yield of the production wells, but also in the surrounding areas to increase the inflow. These techniques are used in hard rock areas.

Ground water conservation techniques. The most common ground water conservation technique is ground water dam/under ground *Bandharas* (Fig. 1.16). In this method a sub-surface barrier across a *nala* (seasonal torrent) bed, stream, micro watershed etc. is constructed to store the water flowing below ground surface in its upstream. Thus, the ground water going out of the basin is arrested and stored within the aquifer. The conditions for adoption of this technique are: (i) the stream is hydraulically connected with phreatic aquifer, (ii) the valley is well defined, and wide with narrow outlet (bottle necked), (iii) the unconfined aquifer occurs within shallow to moderate depth (10 to 20 m) below ground level, and (iv) adequate thickness (minimum 5 m) of aquifer underlying the site is available.

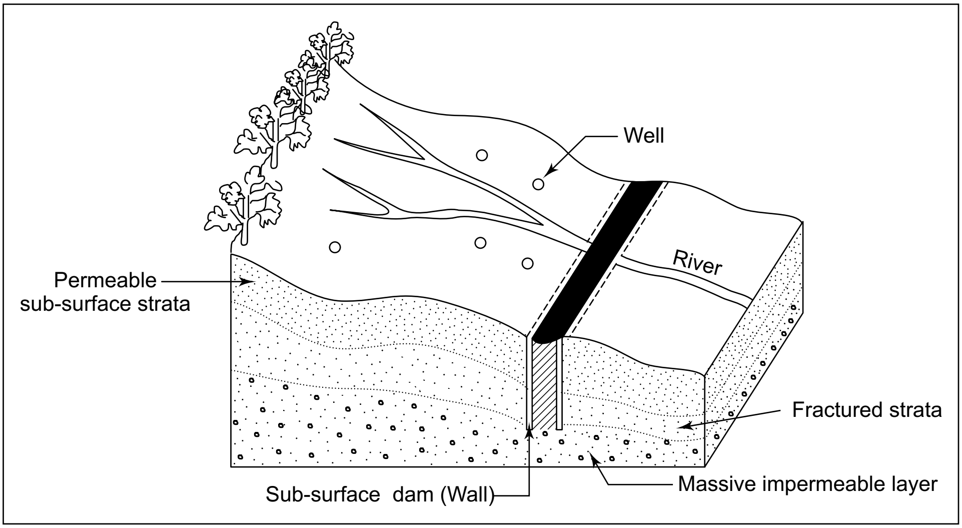

Fig. 1.16 Schematic view (in section) of a sub-surface dam
Source: Based on Central Ground Water Board (1994)

1.13.3 Combination Methods

Under certain hydrological situations a combination of surface and sub-surface recharge methods can be used to enhance the ground water recharge. The combination methods include recharge basin with shaft and induced recharge with connector wells. The recharge basins with shafts are used when rocks exposed on the bottom of the basins are not permeable enough to allow the stored water to infiltrate at a fast rate. Induced recharge with connector wells is suitable in areas comprising of multiple aquifer system existing adjacent to perennial river. In this case connector wells connect the two aquifers.

1.13.4 Selection of Recharge Methods

The selection of suitable recharge method depends upon the hydrogeological characteristics of aquifers, soil characteristics, availability of recharge water, sediment load in recharge water, fluctuations in water levels, rate of discharge and cost/availability of funds. Table 1.11 summarizes the relative suitability of the various types of recharge methods as per topographic and physiographic features.

TABLE 1.11 General Suitability of Recharge Methods

Lithology	Topography	Type of structures feasible
Alluvial or hard rock up to 40 m depth	Plain area or gently undulating area	Spreading pond, ground water dams, irrigation tanks, check dams, percolation tanks, unlinked canal systems
Hard rock down to 40 m depth	Valley slopes	Contour bunds, trenches

(*Contd.*)

TABLE 1.11 *(Contd.)*

Lithology	Topography	Type of structures feasible
Hard rocks	Plateau regions	Recharge ponds
Alluvial or hard rock with confined aquifer	Plain area or gently undulating area	Injection wells, connector wells
-do-	Flood plain deposits	-do-
Hard rock	Foothill zones	Farm ponds, recharge trenches
Hard rocks or alluvium	Forested area	Ground water dams

Source: CGWB, (2000).

1.14 CONJUNCTIVE USE OF GROUND WATER WITH CANAL WATER

Several existing canal irrigation systems suffer from inadequate supplies. The available supply in most canal systems in northern India, for instance, is often less than half the amount needed for intensive agriculture. The total quantity of irrigation water is neither adequate nor supplied satisfactorily and in time. This calls for combined or conjunctive use of surface and ground water, wherever possible.

The conjunctive use of surface and ground water can take the form of augmenting canal supplies by direct pumping of ground water through augmentation tube wells or the direct use of ground water during periods of low canal supplies or canal closures. It can also take the form of irrigating a part of the canal command area exclusively with ground water.

Conjunctive use of surface and ground water has been in practice in India to a limited extent. The practice has been prevalent in the Cauvery delta in Tamil Nadu, the Godavari and Pravara canal systems in Maharashtra, the Ganga Canal in Uttar Pradesh and the Western Jamuna Canal in Haryana and in parts of Punjab. In the Cauvery delta, privately owned filter points have been constructed on a large scale to raise paddy seedlings early in June before the canal system is opened. This facilitates the timely growing of the first paddy crop as well as the timely sowing of the second crop. The filter points also provide irrigation to the rice crop after the canals are closed, thus ensuring a rich harvest. Some farmers also raise summer crops of cotton or groundnut with the help of filter points and give irrigation support to sugarcane crops. Under the Pravara and Godavari canal systems in Maharashtra, a large number of open masonry wells have been constructed by farmers, to supplement canal supplies for growing sugarcane. In Uttar Pradesh, conjunctive use of surface and ground water started as early as 1930, when batteries of tube wells were installed in the tail end of some of the distributaries of the Ganga Canal in Meerut district to meet the great demand for water during periods of low canal supply.

Conjunctive use of surface and ground water may be planned to augment canal supplies, combat waterlogging and facilitate irrigation with poor quality ground water. In the Western Jamuna Canal System in Haryana, tube wells have been constructed along the canal bank to augment canal supplies and lower the ground water table. In countries like Israel and the USA, saline ground water has been used for irrigation, to a limited extent, after diluting with good quality surface water. There is scope for adopting such practices in certain areas of Gujarat, Punjab and Rajasthan where the ground water is brackish.

1.15 LEGAL ASPECTS OF GROUND WATER MANAGEMENT

With the increased use of ground water in irrigation and water supply, the need to regulate its use is becoming increasingly important. Unrestricted abstraction of ground water from an area may lead to its exhaustion. It is necessary that there should be a distinct relationship between the use of ground water and its recharge. In general, the optimum level of ground water extraction is between 70 and 80 per cent of the annual recharge. Further, a well constructed near an existing one, may withdraw the percolating water from the existing well, thus reducing its discharge substantially. There is close interaction between ground water and surface water. It is necessary to prevent pollution of ground water. In irrigation project planning, incorporation of suitable schemes for the conjunctive use of surface and ground water to effectively utilize the water resources of the command area are essential.

In India, statutory provisions for regulating ground water exist only to a very limited extent. Amongst the old laws, only the Irrigation Act of Mysore contained provisions for control by the State, over the construction of wells in areas where public irrigation works are constructed. Under the Act, the State Government notifies such areas. Thereupon, no person can construct any well in the areas without the prior sanction of the Government. The Model Irrigation Bill 1976, prepared by the Ministry of Irrigation, Government of India, in collaboration with the Indian Law Institute, provides for the declaration of certain areas for irrigation works, and a ban on the construction of wells in the area, except with the previous permission of the State Government. Wells which are exclusively for domestic use are exempted from the provisions of the Act. The Punjab Tubewells Act, 1954, provides for the construction and maintenance of state tube wells and supply of water from them.

As the Centre lacks legislative jurisdiction to enact legislation to regulate and control the development and management of ground water it formulated a Model Bill (the first one in 1970, the second in 1992 and third in 2005) and addressed it to all States for possible adoption. It provides for establishment of a Ground Water Authority. The 1970 Bill sought to introduce a licensing mechanism by which the prescribed authority could prohibit a landholder or landowner from constructing wells exceeding a prescribed depth except according to the terms and conditions mentioned therein. The Ground Water Authority was authorized to grant permit for sinking wells for purposes other than domestic use taking into account the availability of ground water. The Ground Water Authority has been vested with the powers to cancel any permits, registrations or licences issued by it. The Authority has been empowered to take legal measures to enforce the legislation.

The 1992 Bill also proposes to establish a Ground Water Authority for the development of ground water. The Bill extended the coverage to all uses including drinking and domestic use and granted exemption for small and marginal farmers from obtaining prior permission of Ground Water Authority for construction of wells provided the well water is to be used exclusively for personal purposes and not for commercial purposes. The bill also provides for registration of existing users and prohibits sinking of new wells in notified areas by the Authority. The Bill contains provision for control over use of ground water through permits, certificate of registration and licence and establishment of ground water notified areas.

In 1997, the Ministry of Environment and Forests constituted Central Ground Water Board as Authority under the Environment (Protection) Act 1986 for the purpose of regulation and control of ground water development and management. The Authority exercises powers under various sections of this Act and regulate indiscriminate boring and withdrawal of ground water in the country and issue necessary regulatory directions with a view to preserve and protect the ground water. In areas of depleting ground water resources, stringent measures are being adopted to check further depletion/pollution of the resource. These include declaration of "Notified Area", permission of Authority for installation of new tubewells in "Notified Area", prohibition on extraction of ground water for commercial purposes, registration of all the existing ground water structures in the "Notified Area" etc.

The Bill 2005 empowers Ground Water Authority for grant of permit to extract and use ground water in notified areas, registration of existing users in notified areas, registration of users of new wells in non-notified areas and registration of drilling agencies. The Authority is also empowered to cancel the permit or certification of registration in case of non-compliance with the conditions stipulated at the time of grant of permit or certificate of registration. The Authority has been conferred extensive powers to enter any property, inspection of well, taking specimens of soil from the well, directing the user of ground water to install water measuring devices or ground water abstraction structure, seeking of information from ground water users, seizing of mechanical equipment used for illegal sinking, etc.

It also empowers Ground Water Authority to issue directives for constructing appropriate rain water harvesting structures in all residential, commercial and other premises having an area of 100 sq. m. or more and take steps for promoting Mass Awareness and Training Programme on Rain Water Harvesting and Artificial Recharge to ground water through government agencies/non-government agencies (NGOs)/volunteer organizations (VOs)/educational institutions/industries/individuals.

The National Water Policy (MOWR, 1987) of the Government of India envisages that planning and development of water resources be governed by national perspectives. In the planning and operation of water resources utilization systems, water allocation priorities have been identified in the following order: drinking water, irrigation, hydro-power, navigation and industrial and other uses. In the planning, implementation and operation of projects, the preservation of the quality of environment and ecological balance are to be given primary consideration. The planning of projects in hill areas shall take into consideration the need to provide drinking water, possibilities of hydro-power development and effecient irrigation system design.

In 2002, the National Water Policy-1987 was revised in view of emergence of many new challenges in the development and management of water resources. The National Water Policy (MOWR, 2002) emphasizes integrated water resources development and management for optimal and sustainable utilization of the available surface and ground water, creation of well-developed information system, use of traditional methods of water conservation, non-conventional methods for water utilization and demand management. The revised policy, integrates quantity and quality aspects as well as environmental considerations for water through adequate institutional arrangements. Besides, 'ecological needs' have been assigned due priority in water allocation. Greater emphasis has been laid on water quality aspects. The policy also stresses involvement of people in project planning and participatory approach in water resources management. On ground water development, the policy emphasizes on need for periodical reassessment of ground water potential, regulation of ground water so that exploitation does not exceed the recharging possibilities, to ensure social equity, integrated and coordinated development of surface water and ground water resources and their conjunctive use and the need to avoid over exploitation of ground water near the coastal areas to prevent the ingress of sea water into fresh water aquifers. The ground water recharge projects should be developed and implemented for improving both the quality and availability of ground water resources.

National Agriculture Policy (MOA, 2000) also promotes rational utilization and conservation of country's abundant water resources according to highest priority to conjunctive use of surface and ground water and focusing on problems of water quality and declining ground water levels.

1.16 GROUND WATER POLLUTION

Water pollution is an undesirable change in physical, chemical or biological characteristics that may or will harmfully affect human life or that of desirable species or industrial processes, living conditions or cultural assets or that will waste or deteriorate our raw material resource.

The sources of ground water pollution are many and varied. Pollution by disease causing micro-organisms occur when human and animal waste containing virus, bacteria and parasites come into contact with ground water. Chemical pollutants can leach into ground water from a variety of sources including hazardous water dumps, sewage, land-treatment sites, injection wells, indiscriminate solid waste disposal. percolation of pesticides and fertilizer from agricultural field and accumulation of industrial waste water on land.

The incidence of ground water pollution is highest in urban areas where large volume of water are concentrated and discharged into relatively small areas. The ground water contaminated, however, is detected only sometime after the sub-surface contamination begins. Fig. 1.17 shows major activities contributing to ground water pollution. The state-wise identified districts having problem of ground water pollution is given in Table 1.12.

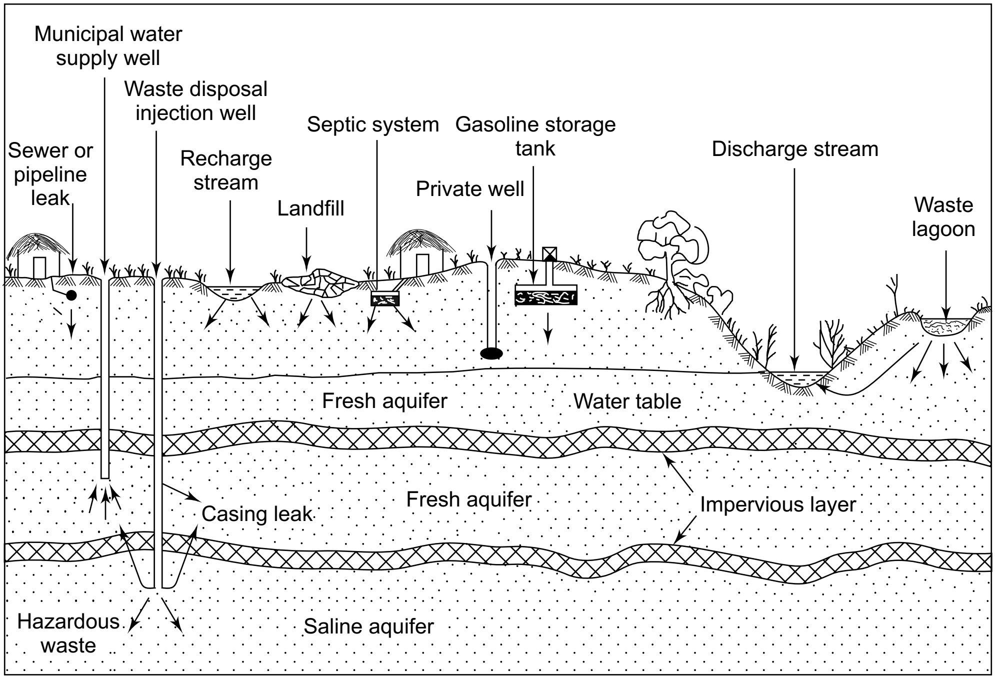

Fig. 1.17 Major sources of ground water contamination

To prevent water pollution, many countries have enacted suitable legislation. For instance, in India, various regulatory and legal measures have been taken over past 30 years. These include the enactment of the water (Prevention and Control of Pollution) Act, 1974 amended in 1988; the Water (Prevention and Control of Pollution) Cess Act, 1977, amended in 1991, the Environment (Protection) Act, 1986. In 2001, the Ministry of Environment & Forests (MOEF), constituted the Water Quality Assessment Authority under the Environment (Protection) Act, 1986 with a view to monitor and take appropriate action for protecting the quality of National Water Resources.

TABLE 1.12 Ground Water Pollution in India

Pollutant	State	Place of occurrences
Salinity (Inland)	Maharashtra	Amravati, Akola
	Bihar	Begusarai
	Haryana	Karnal
	Rajasthan	Barmer, Jaisalmer, Bharatpur, Jaipur, Nagaur, Jalore & Sirohi
	Uttar Pradesh	Mathura
Salinity (Coastal)	Andhra Pradesh	Vishakapatnam
	Orissa	Puri, Cuttak, Balasore
	West Bengal	Haldia & 24 Parganas
	Gujarat	Junagarh, Kachch, Varahi, Banskantha & Surat
Fluoride	Kerala	Palaghat, Krishna, Ananipur, Nellor, Chittoor
	Andhra Pradesh	Cuddapah, Guntur and Nalgonda
	Gujarat	Banskantha, Kachch & Amreli
	Haryana	Hissar, Kaithal & Gurgaon
	Orissa	Bolangir, Bijapur, Bhubaneswar and Kalahandi
	Punjab	Amritsar, Bhatinda, Faridkot, Ludhiana & Sangrur
	Rajasthan	Nagaur, Pali, Sirohi, Ajmer & Bikaner
	Tamil Nadu	Chengalput, Madurai
	Uttar Pradesh	Unnao, Agra, Aligarh, Mathura, Ghaziabad, Meerut & Rai Baraili
Sulphide	Orissa	Balasore, Cuttack & Puri
Iron	Uttar Pradesh	Mirzapur
	Assam	Darrang, Jorhat, Kamrup
	Orissa	Bhubaneswar
	Bihar	East Champaran, Muzaffarpur, Gaya, Manger, Deoghar & Madubani
	Rajasthan	Bikaner, Alwar, Bharatpur
	Tripura	Dharmnagar, Kailasanar, Ambasa, Amarpur & Agartala
	West Bengal	Madnipur, Howrah, Hoogly and Bankura
Maganese	Orissa	Bhubaneswar, Athgaon
	Uttar Pradesh	Moradabad, Basti, Rampur & Unnao
Arsenic	West Bengal	Murshidabad, Nadia, 24 Parganas
Nitrate	Bihar	Patna, East Champaran, Palamu, Gaya, Nalanda, Nawada and Banka
	Andhra Pradesh	Vishakapatnam, East Godavari, Krishna, Prakasam, Nellor, Chittoor, Anantapur, Cuddapah, Kurnool, Khamam and Nalgonda
	Delhi	Naraina, Shahdara (Blocks)
	Haryana	Ambala, Sonepat, Jind, Gurgaon, Faridabad & Hissar
	Himachal Pradesh	Kulu, Solan, Una
	Karnataka	Bidar, Gulbarga and Bijapur
	Madhya Pradesh	Sehore, Bhopal & (West & Central Part of state)
	Maharashtra	Jalna, Beed, Nanded, Latur, Osmanabad, Solapur Satara, Sangli and Kolhapur

(*Contd.*)

TABLE 1.12 *(Contd.)*

Pollutant	State	Place of occurrences
	Punjab	Patiala, Faridkot, Firozpur, Sangrur & Bhatinda
	Rajasthan	Jaipur, Churu, Ganganagar, Bikaner, Jalore, Barmer, Bundi and Sawaimadhopur
	Tamil Nadu	Coimbatore, Penyar and Salem
	West Bengal	Uttar Dinajpur, Malda, Birbhum, Murshidabad, Nadia, Bankura and Purulia
Chloride	Karnataka	Dharwad, Belgaum
	Madhya Pradesh	Bhind, Shagapur and Sehore
	Maharashtra	Solapur, Satara, Amravati, Akola & Jalore
	Rajasthan	Barmer, Jaisalmer, Jodhpur & Jalore
	West Bengal	Contai, Digha, Haldia
Zinc	Andhra Pradesh	Hyderabad, Osmania University campus
	Delhi	R.K. Puram
	Rajasthan	Udaipur
Chromium	Punjab	Ludhiana

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SHORT QUESTIONS

I. State True (T) or False (F).

1. Amongst the different components of water resources, ground water resource is the most widely distributed, dependable and pure.
2. The total amount of water contained in the earth can be increased or decreased.
3. A ground water aquifer is a porous formation below ground that will yield enough water for economical use.
4. In general, the shape of the water table tends to follow the topography of the ground surface.
5. The piezometric surface is analogous to the water table in unconfined aquifer.
6. In general, higher the porosity, higher is the permeability.
7. Moisture content of a soil can exceed porosity.
8. Clay can hold as much water as the sand can.
9. The capillary fringe will be more in sands than clays.
10. The porosity of sand is more than clay.
11. A phreatic aquifer is also called a water table aquifer.

12. A perched aquifer is a special case of confined aquifer.
13. A semi-confined aquifer is completely saturated aquifer.
14. The hydraulic conductivity of semi-pervious layer is more than semi-confined aquifer.
15. The water held to surface of soil particles by surface tension is called hygroscopic water.
16. Sedimentary rocks are formed from eruptive rocks.
17. Basalt is a form of volcanic rock.
18. Crystalline rocks are good water bearers.
19. About 60 per cent of the rainfall in most parts of India is contributed by south-west monsoon.
20. The depth of the water table fluctuates from season to season.
21. The piezometric head in a leaky aquifer is always greater than the phreatic head.
22. The leaky aquifer is bounded above by a semi-pervious layer.
23. The unconsolidated formations account for about 40 per cent of total usable ground water resources of India.
24. The major part of India consists of hard rock formations.
25. The rocks in consolidated formations have plenty of ground water.
26. The flow and storage of ground water in hard rock is due to secondary porosity.
27. Geophysical investigations give direct evidence of aquifer presence.
28. Geophysical methods are used as surface techniques only.
29. Test drilling is more reliable than geophysical methods to learn about the character of the formation.
30. Clean sand saturated with fresh water shows relatively high resistivity.
31. The cable tool method is slower but provide more accurate information about the formation.
32. Electric logging is applicable only to cased bore holes.
33. Water divining is the art of detecting under ground water by dowsing rod.
34. Gamma-ray logging is influenced by changes in water quality.
35. In denser material the shock wave travel faster.
36. A seismograph shows the time of arrival of shock wave over a measured distance from the point of application of the shock.
37. Ground water has lower salt content than surface water.
38. A *p*H value of 8 indicates acidic solution.
39. Parts per million is numerically equivalent to milligrams per cubic centimetre.
40. One mmhos/cm is equivalent to one dS/m.
41. Presence of high concentration sodium and chloride ions in water results in water of low salinity.
42. Dug wells generally draw water from more than one aquifer.
43. Boring through the bottom of the dug wells help in augmenting their yield.
44. Bore wells are unlined tube wells.
45. Higher alkalinity ground water are mostly encountered in arid parts of Rajasthan, Gujarat and Haryana.
46. Stream modification is essentially a sub-surface technique for artificial recharge.
47. In area with uneven land surface-furrow method can be used as a recharge method.
48. Surface spreading techniques can be used for recharge of ground water irrespective of the geologic nature of the ground water basin.
49. The runoff conservation structures can increase the ground water recharge.
50. Sub-surface techniques are used to recharge the confined aquifer.
51. Bandharas is the most common ground water conservation technique.
52. The incidence of ground water pollution is higher in rural areas.

Ans. True 1, 3, 4, 5, 8, 11, 13, 17, 20, 21, 22, 24, 26, 29, 30, 31, 33, 35, 36, 40, 43, 44, 47, 49, 50, 51.

II. Select the correct answer.

1 An aquifer is a geologic formation that
(a) contain water but does not transmit (b) does not contain water
(c) contain water and also transmit (d) is a rock outcrop

2. A localized water body above the water table in an unconfined aquifer is known as
(a) confined aquifer (b) perched aquifer
(c) unconfined aquifer (d) artesian aquifer

3. An aquifer which is bounded by an impermeable layer at the bottom and semi-pervious layer at the top is known as
(a) semi-confined aquifer (b) confined aquifer
(c) artesian aquifer (d) unconfined aquifer

4. An imaginary surface obtained by joining the water levels in several observation wells penetrating a confined aquifer is called
(a) phreatic surface (b) piezometric surface
(c) capillary frinze (d) water table surface

5. The water held by surface tension to soil particles is known as
(a) gravitational water (b) hygroscopic water
(c) drainage water (d) capillary water

6. The geological formation found in major parts of India is
(a) unconsolidated (b) consolidated
(c) semi-consolidated (d) alluvium

7. A common bore hole geophysical method is
(a) electric resistivity (b) seismic refraction
(c) gamma-ray logging (d) water divining

8. The major source of ground water replenishment is
(a) seepage from water bodies (b) precipitation
(c) deep percolation from irrigated fields (d) artificial ground water recharge

9. Which of the following constituents found in ground water is most likely associated with agricultural land use?
(a) Nitrate (b) Sulphate
(c) Arsenic (d) Chromium

10. The flow of water downward from the land surface into and through the soil layers is
(a) percolation (b) recharge
(c) infiltration (d) permeability

11. Most water on the land surface is returned to the atmosphere by
(a) sublimation (b) evapotranspiration
(c) Precipitation (d) runoff

12. Which of the following reservoirs contains the most water?
(a) atmosphere (b) oceans and seas
(c) ground water (d) lakes and reservoirs

13. With respect to earth's land surface, which of the following expressions is correct?
(a) precipitation = evaporation - runoff (b) precipitation = evaporation + runoff
(c) precipitation = runoff - evaporation (d) precipitation = evaporation* runoff

14. Most ground water withdrawn in India is used for
(a) industry (b) drinking
(c) swimming pools (d) irrigation

15. Which pollutant is removed as ground water moves through the soil profile?
    (a) dissolved pollutants
    (b) suspended particles
    (c) organic chemicals
    (d) agro-chemicals
16. What is the most reasonable course against ground water pollution?
    (a) prevention
    (b) filtration
    (c) treatment
    (d) regulation
17. The near surface zone where all pores are filled with water is called
    (a) the vadose zone
    (b) the saturated zone
    (c) the water table
    (d) the aquifer
18. The top of the water saturated zone is known as
    (a) the aquifer
    (b) the hydraulic head
    (c) the aquitard
    (d) the water table
19. Which factor most affect the piezometric surface for artesian aquifer?
    (a) slope
    (b) shape
    (c) volume
    (d) pressure
20. How much of total land area of India is covered by semi-consolidated formations?
    (a) 5 per cent
    (b) 10 per cent
    (c) 15 per cent
    (d) 20 per cent
21. Electric logging is used by well drillers to
    (a) measure the electrical resistivity of different water bearing strata in the bore hole
    (b) locate buried electrical lines before well drilling begins
    (c) record the well drilling progress
    (d) repair damage to the aquifer
22. The main reason for monitoring ground water levels is to
    (a) assure that all ground water users pump equal quantities of water
    (b) detect declining ground water levels
    (c) detect unwanted change in ground water quality
    (c) investigate factors that affect ground water flow
23. Water that is good enough to drink is called
    (a) ground water
    (b) potable water
    (c) surface water
    (d) artesian water
24. In highly alkali water the value of residual sodium carbonate is
    (a) < 2 meq/l
    (b) 2.0–3.0 meq/l
    (c) 3.0–4.0 meq/l
    (d) > 4.0 meq/l
25. Which of the following items cause turbidity in water?
    (a) hardness
    (b) *p*H
    (c) suspended material
    (d) salinity
26. Good aquifers include all of the following except
    (a) sandstone
    (b) limestone
    (c) crystalline
    (d) basalt

Ans. 1. (c) 2. (b) 3. (a) 4. (b) 5. (d) 6. (b) 7. (c) 8. (b) 9. (a) 10. (a) 11. (b) 12. (b) 13. (b) 14. (d) 15. (b) 16. (a) 17. (b) 18. (d) 19. (d) 20. (a) 21. (a) 22. (b) 23. (b) 24. (d) 25. (c) 26. (a)

2

Hydraulics of Wells

Irrigation wells operate according to certain fundamental hydraulic principles. Water flows into the well from the surrounding aquifer because the pumping of the well creates a difference in head. Before pumping, the water in the well stands at a height equal to the static water level or static water pressure in the saturated layer around the well. When pumping starts, the water in the well is drawn down and the water starts to flow into the well from the water-bearing formation because the water level or pressure inside the well during pumping is lower than in the aquifer outside the well. This pressure difference is the 'drive' that causes the water to move through the pores of the sand or through crevices towards the well. The closer the water gets to the well, the faster it has to move, because the area through which it has to travel is continuously decreasing.

2.1 DEFINITIONS

2.1.1 Static Water Level

The level at which the water stands in a well before pumping starts is called the static water level. It is generally the level of the water table, except in case of artesian wells where the static level may be above the water table. The pressure of water at the static water level is atmospheric. The static water level is generally expressed as the vertical distance from the ground surface to the water level in the well.

2.1.2 Piezometric Surface

The piezometric surface is the height at which water will stand in a piezometer or pipe open at the end and which extends into the aquifer. The height h to which the water will rise in the pipe from the base is equal to the pressure p at the bottom of the pipe divided by the unit weight w of water,

$$h = \frac{p}{w} \tag{2.1}$$

2.1.3 Pumping Water Level

This is the level at which water stands in a well when pumping at any given rate. This level is variable and changes with the quantity of water being pumped.

2.1.4 Drawdown

Drawdown at any instant is the difference between the static water level and the pumping water level. Drawdown affects the yield of well. The maximum practical drawdown in a tube well is limited to the pumping water level reaching the top of the well screen.

2.1.5 Area of Influence

When the water is pumped out of the well, it gets supply from the surrounding formations, and the water table or piezometric surface, depending on the type of aquifer, is lowered. There is, thus an imaginary inverted cone formed around the well having the static water level as base and pumping level as apex (Fig. 2.1). The conical shape is known as cone of depression. The area which gets affected by the pumping of the well is called the *area of influence*. The boundary of the area of influence is called the *circle of influence*. The radius of the circle of influence is called the *radius of influence*.

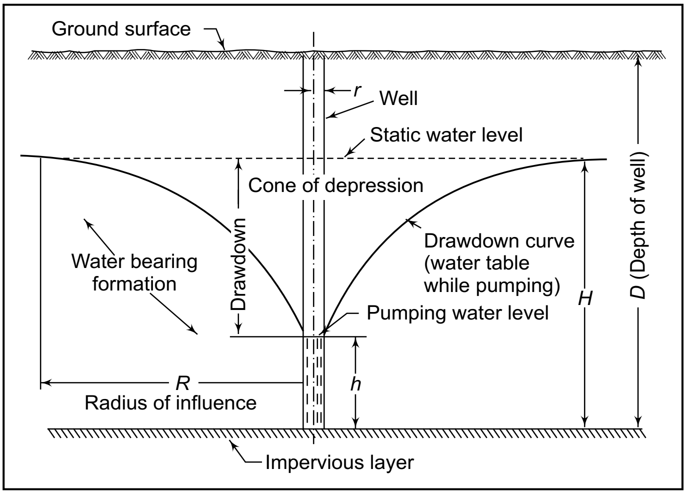

Fig. 2.1 Definition sketch illustrating the hydraulics of flow into a well penetrating an unconfined aquifer

As more and more water is pumped out of the well, it takes more water from storage. As a result, the radius of influence gets extended till a position is reached when the rate of discharge from the well becomes equal to the rate of recuperation from the area around the well. It is at this instant that the cone of depression gets stabilized. This equilibrium condition changes when the discharge rate is increased or decreased.

2.1.6 Well Yield

The yield of a well is the volume of water discharged from it per unit time. It is commonly expressed in litres per second or per minute, or cubic metres per minute, hour or day.

2.1.7 Specific Capacity

Specific capacity of a well is its yield per unit of drawdown. It is usually expressed as litres per minute per metre of drawdown. Dividing the yield by the drawdown, each measured at the same time, gives the specific capacity.

2.1.8 Open Wells

Open wells are dug down to the water-bearing strata. They derive water from the formations close to the ground surface. The large diameter of open wells permits the storage of a large quantity of water.

2.1.9 Tube Wells

Tube wells are constructed by fixing a pipe below the ground surface and passing through different geological formations consisting of water-bearing and non-water-bearing strata. Blind pipes are located against the non-water-bearing strata, and perforated pipes or well screens are placed against the aquifers. In *cavity wells*, however, screens are not used. The well casing rests over a confined water-bearing formation of sand and gravel. Water enters the well through the bottom only.

2.1.10 Filter Points

In deltaic regions, where aquifer formations are of coarse sand and gravel, tube wells are shallow and consist of a well screen and a short length of casing pipe. Such wells are called filter points.

2.2 AQUIFER CHARACTERISTICS INFLUENCING YIELD OF WELLS

The properties of the aquifer that influence well performance are depth, areal extent, number of water bearing formations exposed to the well, and the hydraulic properties of the aquifer. An aquifer performs two functions, viz., storage and as a conduit. The properties of an aquifer may be expressed in terms of its hydraulic conductivity, transmissibility, storage coefficient and specific yield. In case of semi-confined aquifers, two additional properties viz., leakage factor and hydraulic resistance, are also important.

2.2.1 Hydraulic Conductivity

The hydraulic conductivity K, as applied to an aquifer, is defined as the rate of flow of water, in litres per day, through a horizontal cross-sectional area of one square metre of the aquifer, under a hydraulic gradient of one metre per metre at the prevailing temperature of water. The first rational analysis of the movement of water through sand was carried out by Darcy (1856), who established the relationship as expressed in Eq. (2.2), which formed the basis of all studies of flow through porous media. Darcy's experiments showed that the flow of water through a column of saturated sand is proportional to the difference in hydraulic heads at the ends of the column and inversely proportional to the length of the column. This is known as Darcy's law and is expressed as

$$v = \frac{K(h_1 - h_2)}{l} \tag{2.2}$$

in which,

v = velocity of flow, m/day

K = hydraulic conductivity, depending upon the properties of the sand and the liquid, m/day

$h_1 - h_2$ = difference in hydraulic head, m

l = distance along the flow path between the points h_1 and h_2. The difference in hydraulic head, $(h_1 - h_2)$, divided by the distance, l, along the path of fluid flow is called the hydraulic gradient, i,

Thus,
$$v = Ki \tag{2.3}$$

Often, the quantity of flow may be of greater interest than the velocity. Hence, in terms of quantity of flow, Darcy's law may be expressed as

$$Q = av = Kia \tag{2.4}$$

in which,

Q = volume of water discharged in standard length of time, usually expressed as m^3/day

a = cross-sectional area through which water moves, m^2.

The value of K can be obtained by laboratory tests of samples of the formation material. For field use, however, it is more appropriate to determine the values of K from pumping test data, as discussed in Secs. 2.4 and 2.5.

2.2.2 Transmissibility

As shown in Eq. (2.4), the flow q through each metre width of the aquifer is,

$$q = Kbi \tag{2.5}$$

in which,

K = the average hydraulic conductivity of the material from top to bottom of the aquifer, m/day

b = thickness of the aquifer, m

i = hydraulic gradient.

The transmissibility, T may be defined as the product of K and b. It represents the water transmitting capability of the entire thickness of confined and semi-confined aquifers. Thus, transmissibility Kb is used to calculate how much water will move through the water bearing formation. It is defined as the rate at which water will flow through a vertical strip of the aquifer, one metre wide and extending through the full saturated thickness of the aquifer, under a unit hydraulic gradient. The value of T ranges from less than 12,000 litres per day per metre to nearly 12,00,000 litres per day per metre. A tube well having a value T of 1,20,000 litres per day per metre or more is considered satisfactory as an irrigation well.

When the transmissibility, T, is introduced in Eq. (2.4), the flow through a vertical section of an aquifer may be expressed as:

$$Q = Tiw \tag{2.6}$$

in which, w is the width of the vertical section through which the flow occurs. The value of T can be determined from aquifer pumping tests by measuring, in one or more wells, the decline of head with time under the influence of a constant pumping rate (Secs. 2.4 and 2.5).

2.2.3 Coefficient of Storage

The storage properties of confined and semi-confined aquifers are expressed by the coefficient of storage S, which is defined as the volume of water the aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to the surface (Fig. 2.2). Water recharged to or discharged from an aquifer represents a change in the storage volume within the aquifer. In a confined aquifer, the coefficient of storage is a result of compression of the aquifer and expansion of the contained water, as a result of reduced pressure due to pumping. The value of S, which is a dimensionless quantity, ranges from 0.00001 to 0.001 for confined aquifers. It may be determined from pumping tests of wells (Secs. 2.4 and 2.5).

2.2.4 Specific Yield

Specific yield is the property of an unconfined aquifer. It is defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface (Fig. 2.3). Under unconfined aquifer conditions, ground water is derived from storage by gravity drainage of the voids in the portion of the aquifer that has been unwatered by pumping.

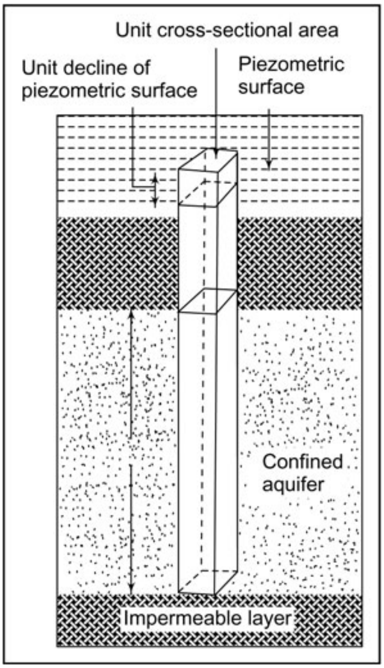

Fig. 2.2 Definition sketch of storage coefficient

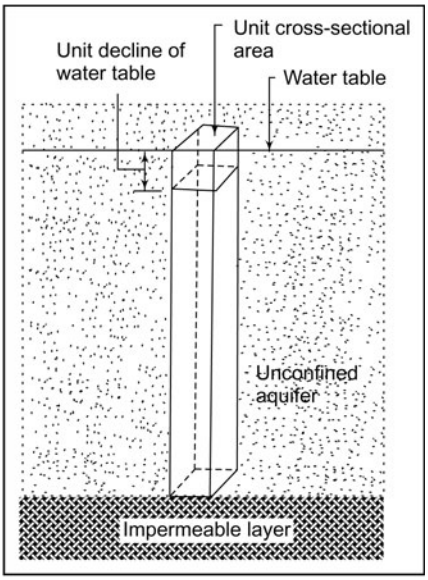

Fig. 2.3 Definition sketch of specific yield

When water is drained from an aquifer by gravity only part of the total volume stored in its pores is released. The quantity of water that a unit volume of the aquifer will yield when drained by gravity is called its specific yield. The part of the water that is retained in the aquifer mass is held against the force of gravity by molecular attraction and capillarity. The quantity of water that a unit volume of aquifer retains when subjected to gravity drainage is called its specific retention. Both specific yield and specific retention are expressed as fractions or percentages. The sum of the specific yield and specific retention equals the porosity of the aquifer. For example, if 0.10 m^3 of water is drained from 1 m^3 of saturated sand, the specific yield of the sand is 0.10, or 10 per cent. Assuming that the porosity of the sand is 28 per cent, its specific retention is 0.18, or 18 per cent. (In American literature, the term storage coefficient and specific yield are often used synonymously).

2.2.5 Hydraulic Resistance

The hydraulic resistance, also called the reciprocal leakage factor or resistance against vertical flow, is a property of a semi-pervious layer of the semi-confined aquifer. It is the ratio b'/K' in which b' is the saturated thickness of the semi-pervious layer and K' is its hydraulic conductivity for vertical flow. It characterises the resistance of the semi-pervious layer to upward or downward leakage. It is designated by the symbol c and has reduced dimensions of time. When the value of c equals infinity, the layer is considered to be impervious. When the value of c of any lithological section is equal to or near to zero, the layer is considered an aquifer. The value of the hydraulic resistance of a semi-pervious layer is evaluated on the basis of pumping test data, using the following equation

$$c = \frac{B^2}{Kb} \tag{2.7}$$

in which,

c = hydraulic resistance, days
B = leakage factor, m
K = hydraulic conductivity of the aquifer, m/day
b = thickness of the horizontal pervious stratum, confined between the horizontal semi-pervious and impervious layers, m

The value of c of a semi-pervious layer generally ranges between 100 and 10,00,000 minutes.

2.2.6 Leakage Factor

The leakage factor is defined as

$$B = \sqrt{(Kbc)} \tag{2.8}$$

It determines the distribution of leakage into or from the semi-pervious layer. High values of leakage factor indicate a great resistance of the semi-pervious strata to flow, as compared to the resistance of the aquifer itself. This factor has the dimension of length, L. The value of B can be determined by the pumping test data of the semi-confined aquifer.

Example 2.1 In an area, 1 km^2 in extent, the initial water table was at a depth of 25 m below ground surface. After applying an irrigation, the water table rose to a depth of 24 m. Later on, an amount of

3×10^5 m^3 ground water was pumped out resulting in drop in water table by 2.2 m. Find out specific yield of the aquifer and volume of recharge during irrigation.

Solution Volume of aquifer drained in lowering

$$\text{water table by 2.2 m} = \text{Area of aquifer} \times 2.2$$

$$= 1 \times 10^6 \times 2.2 = 2.2 \text{ M m}^3$$

$$\text{Specific yield of aquifer} = \frac{\text{Volume of water pumped}}{\text{Volume of aquifer drained}}$$

$$= \frac{3 \times 10^5}{2.2 \times 10^6} = 0.136$$

$$\text{Volume of recharge} = \text{Area of aquifer} \times \text{rise in water table} \times \text{specific yield}$$
$$= 1 \times 10^6 \times 1.0 \times 0.136 = 136000 \text{ m}^3$$

2.3 STEADY STATE RADIAL FLOW

The flow is said to be steady when no change occurs with time, i.e.

$$\frac{dv}{dt} = 0$$

where, v = velocity of flow, m/s, and

t = time, s

Steady state flow occurs when there is equilibrium between the discharge of the pumped well and the recharge of the aquifer by an outside source.

Flow conditions differ for unconfined and confined aquifers, and need to be considered separately.

2.3.1 Steady State Flow to Wells in Unconfined Aquifers

An equation for steady radial flow to a well in an unconfined aquifer can be derived with the Dupuit assumptions which state (1) that the velocity of flow is proportional to the tangent of the hydraulic gradient, instead of the sine as defined in Eq. (2.2), and (2) that the flow is horizontal and uniform everywhere in a vertical section.

The flow is assumed two dimensional to a well centered on a circular island and penetrating a homogeneous and isotropic aquifer. As shown in Fig. 2.4, the well completely penetrates the aquifer to the horizontal base. The well discharge Q at any distance r is expressed as

$$Q = Kia = 2\pi rhK \frac{dh}{dr}$$

or

$$hdh = \frac{Q}{2\pi K} \frac{dr}{r}$$

Integrating for boundary conditions at the well, $h = h_w$ at $r = r_w$ and $h = H$ at $r = R$

$$\int_{h_w}^{H} h dh = \frac{Q}{2\pi K} \int_{r_w}^{R} \frac{dr}{r}$$

or
$$H^2 - h_w^2 = \frac{Q}{\pi K} \ln (R/r_w)$$

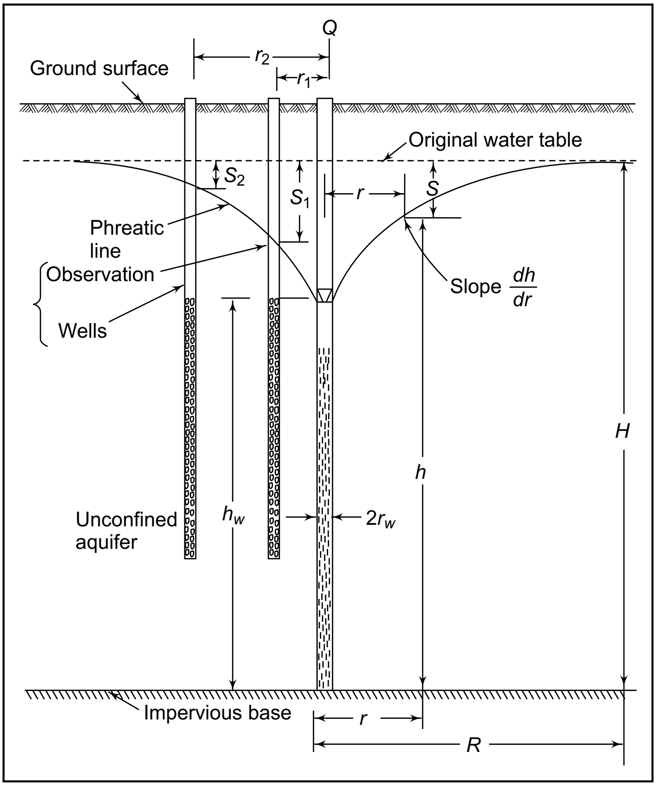

Fig. 2.4 Definition sketch illustrating steady state flow into a fully penetrating well in an unconfined aquifer

or
$$Q = \frac{\pi K(H^2 - h_w^2)}{\ln (R/r_w)}$$

$$= \frac{\pi K(H + h_w)(H - h_w)}{\ln (R/r_w)} \quad (2.9)$$

in which,

Q = constant discharge rate, m^3/s

H = original elevation of the water surface, measured from the impervious base, m

h_w = depth of water in the well, measured from the impervious base, m

R = radius of influence of the well field, m

K = hydraulic conductivity of the aquifer, m/s
r_w = radius of the well, m

Thiem (1870) established the practicability of Eq. (2.9). He showed that beyond a certain distance from the well, the drawdown of the phreatic surface from the original ground water table became negligible. The Dupuit-Thiem theory, stated above, is of paramount importance in well hydraulics.

Evaluation of Hydraulic Properties

The hydraulic properties of the aquifer can be evaluated by using Eq. (2.9) for steady state conditions.

Let the steady state drawdown at the observation wells be s_1 and s_2 and r_1 and r_2 the distances of the observation wells from the centre of the test well (Fig. 2.4).

Since $$h = H - s$$

Eq. (2.9) can be transformed as

$$Q = \frac{\pi K(h_2^2 - h_1^2)}{\ln(r_2 / r_1)}$$

which can be expanded into

$$Q = \frac{\pi K[(H - s_2)^2 - (H - s_1)^2]\, 2H / 2H}{\ln(r_2 / r_1)}$$

in which h_1 and h_2 are elevations of water surface, measured from impervious base at observation wells 1 and 2.

Replacing $s - s^2/2H$ by s' = the corrected drawdown, yields

$$Q = \frac{2\pi KH(s_1' - s_2')}{\ln(r_2 / r_1)} \tag{2.10}$$

in which,

$$s_1' = s_1 - s_1^2/2H$$

$$s_2' = s_2 - s_2^2/2H$$

s_1' and s_2' are corrected steady-state drawdowns at points 1 and 2, respectively,

or $$Q = \frac{2\pi T(s_1' - s_2')}{\ln(r_2 / r_1)}$$

in which,

$T = KH$ = assumed transmissibility of the aquifer, m^2/s.

or $$T = \frac{Q \ln(r_2 / r_1)}{2\pi (s_1' - s_2')} \tag{2.11}$$

The values of transmissibility and hydraulic conductivity can be estimated using Eq. (2.11) only when the drawdown in the aquifer is small in relation to the thickness of the saturated portion of the aquifer.

2.3.2 Steady State Flow to Wells in Confined Aquifer

To derive the radial flow equation for a well completely penetrating a confined aquifer (Fig. 2.5), Dupuit used Eq. (2.4). The flow is assumed two-dimensional to a well centred on a circular island and penetrating a homogeneous and isotropic aquifer. Since the flow is horizontal everywhere, the Dupuit assumptions apply without error. Using plane polar coordinates, with the well as the origin, the well discharge Q, at any distance r, when the thickness of the aquifer is b, is determined as follows:

$$Q = Kia = 2\pi rbK \frac{dh}{dr}$$

or

$$dh = \frac{Q}{2\pi Kb} \frac{dr}{r}$$

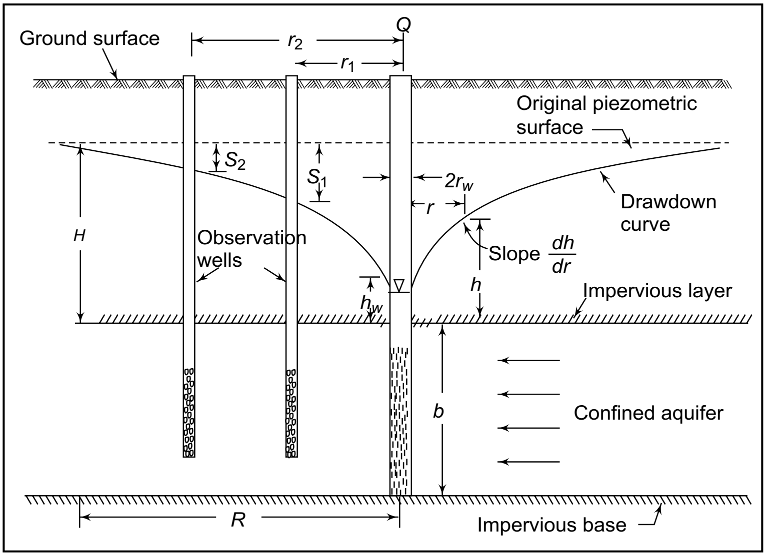

Fig. 2.5 Definition sketch illustrating the hydraulics of flow in a fully penetrating well in a confined aquifer

Integrating for the boundary conditions at the well, $h = h_w$ at $r = r_w$ and $h = H$ at $r = R$ at the extremity of the area of influence,

$$\int_{h_w}^{h} dh = \frac{Q}{2\pi Kb} \frac{dr}{r} \int_{r_w}^{h} \frac{dr}{r}$$

$$H - h_w = \frac{Q}{2\pi Kb} \ln (R/r_w)$$

After rearranging,

$$Q = \frac{2\pi Kb (H - h_w)}{\ln (R/r_w)} \tag{2.12}$$

in which,

b = thickness of the horizontal pervious stratum confined between two horizontal impervious strata, m

The other variables are the same as defined in Eq. (2.9). Equation (2.12) can be used to evaluate the hydraulic properties of an aquifer, based on the measurements made during a pumping test. This equation is also known as Dupuit-Thiem equation. Thiem (1870), who worked independently of Dupuit, derived Eq. (2.9) and (2.12), based on the following assumptions which were more precisely defined than those of Dupuit:

1. The aquifer has a seemingly infinite areal extent.
2. The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.
3. The pumped well penetrates the entire thickness of the aquifer and receives water from its entire thickness by horizontal flow.
4. Flow to the well is in steady state.

Evaluation of Hydraulic Properties

To determine the hydraulic properties of the water-bearing formations, in case of wells in a confined aquifer, any one of the following two procedures can be used:

Procedure 1. On a semi-logarithmic paper, the observed drawdown in each piezometer or observation well is plotted against the corresponding time, with drawdown on the vertical axis, on a linear scale and with time on the logarithmic scale. The time drawdown curve of each piezometer, that best fits the points is drawn. It will be observed that the curves of the different piezometers run parallel for the later time data and thus, the mutual distance is constant. This implies that the hydraulic gradient is constant and the flow in the aquifer can be considered to be in a steady state. The values of the steady state drawdown of two piezometers are substituted in Eq. (2.12) together with the corresponding values of r and the known value Q to solve for the transmissibility $T = Kb$.

$$Q = \frac{2\pi T(s_1 - s_2)}{\ln (r_2 / r_1)} \tag{2.13}$$

where, s_1 and s_2 are the values of drawdown of the piezometers and r_1 and r_2 distances from the centre of the well, respectively.

The same process should be repeated for all possible combinations of piezometers to get a more precise value of T. Theoretically the results should show a close agreement. However, an average value can be used as the results usually give slightly different values of T.

Procedure 2. The observed steady state drawdown s of each observation well is plotted against the distance r between the pumped well and the piezometer on a semi-logarithmic paper. The distance is plotted on the horizontal axis on a logarithmic scale, and the drawdown on the vertical axis on a linear scale. The best-fitting straight line is drawn through the plotted points, which is the distance-drawdown curve (Fig. 2.6). The slope of the distance-drawdown curve for logarithmic cycle of distance, Δs, is determined. The value of Δs, when substituted in Eq. (2.13), gives the following relationship:

$$Q = \frac{2\pi T \Delta s}{2.30} \tag{2.14}$$

The values of transmissibility and hydraulic conductivity can be predicted by substituting the values of Q and Δs in Eq. (2.14).

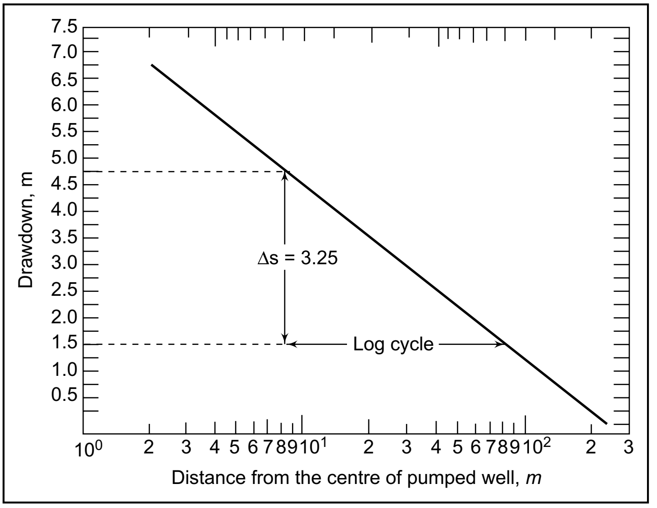

Fig. 2.6 Distance-drawdown curve (on semi-log paper) for determining the transmissibility and hydraulic conductivity of aquifers (Example 2.4)

Example 2.2 A 25 cm diameter well in an unconfined aquifer is pumped at a uniform rate of 3000 1/min. The drawdowns observed at 1 m and 100 m distances from the centre of the well are 8 m and 0.4 m, respectively. Determine the hydraulic conductivity of the water-bearing strata, assuming the thickness of the saturated part of the aquifer is 25 m.

Solution

$$Q = 3 \text{ m}^3/\text{min}$$

$$r_1 = 1 \text{ m}$$

$$r_2 = 100 \text{ m}$$

$$h_1 = H - s_1 = 25 - 8 = 17 \text{ m}$$

$$h_2 = H - s_2 = 25 - 0.4 = 24.6 \text{ m}$$

$$K = \frac{Q}{\pi (h_2^2 - h_1^2)} \ln\left(\frac{r_2}{r_1}\right)$$

$$= \frac{3}{\pi (24.6^2 - 17^2)} \ln\left(\frac{100}{1}\right)$$

$$= 0.0139 \text{ m/min}$$

Example 2.3 A 10 cm diameter well penetrates a 10 m thick confined aquifer. The steady state drawdowns were found to be 2.5 and 0.05 m at distances of 10 m and 40 m, respectively, from the centre of the well, when the well was operated with a constant discharge rate of 125 1/min for 12 h. Using the Dupuit-Thiem equation, calculate the transmissibility and hydraulic conductivity of the aquifer.

Solution

$$r_1 = 10 \text{ m}$$
$$r_2 = 40 \text{ m}$$
$$s_1 = 2.5 \text{ m}$$
$$s_2 = 0.05 \text{ m}$$
$$Q = 0.125 \text{ m}^3/\text{min}$$

Using Eq. (2.13),

$$T = \frac{Q \ln (r_2 / r_1)}{2\pi (s_1 - s_2)}$$

$$= \frac{0.125 \ln (40/10)}{2\pi (2.5 - 0.05)}$$

$$T = 0.0113 \text{ m}^2/\text{min}$$

$$\text{Hydraulic conductivity} = T/b$$

$$= \frac{0.0113}{10}$$

$$= 0.00113 \text{ m/min}$$

Example 2.4 A well in a confined aquifer is pumped at a constant rate of 1500 1/min. The drawdowns were measured in the piezometer after 60 min of pumping. The results were as follows:

Distance of piezometer from centre of well, m	3	9	40	90
Drawdown, m	6.5	4.75	3.0	1.5

Calculate the aquifer transmissibility, assuming steady state drawdown.

Solution

By Procedure 2 (Thiem method), the values of s and r are plotted on a semi-log paper, as shown in Fig. 2.6. The slope of the best fitting straight line is equal to a drawdown difference of 3.25 m per log cycle of r (Δs). Substituting the values of Δs and Q in Eq. (2.14)

$$T = \frac{2.30 Q}{2\pi \Delta s} = \frac{2.3 \times 1.50}{2 \times \pi \times 3.25}$$

$$= 0.169 \text{ m}^2/\text{min}$$

Example 2.5 Using the test results given in Example 2.4, calculate the transmissibility values of different sections and the average transmissibility, using Thiems Procedure 1.

Solution

$$T = \frac{Q}{2\pi(s_1 - s_2)} \ln \left(\frac{r_2}{r_1}\right)$$

Solution 1:

$r_1 = 3$ m

$r_2 = 9$ m

$s_1 = 6.5$ m

$s_2 = 4.75$ m

$$T = \frac{1.5}{2\pi(6.5 - 4.75)} \ln\left(\frac{9}{3}\right)$$

$= 0.149$ m^2/min

Solution 2:

$r_1 = 9$ m

$r_2 = 40$ m

$s_1 = 4.75$ m

$s_2 = 3.0$ m

$$T = \frac{1.5}{2\pi(4.75 - 3)} \ln\left(\frac{40}{9}\right)$$

$= 0.203$ m^3/min

Solution 3:

$r_1 = 40$ m

$r_2 = 90$ m

$s_1 = 3$ m

$s_2 = 1.5$ m

$$T = \frac{1.5}{2\pi(3.0 - 1.5)} \ln\left(\frac{90}{40}\right)$$

$= 0.129$ m^2/min

Average transmissibility $= (^1/_3)\,(0.149 + 0.203 + 0.129)$

$= 0.160$ m^2/min

2.3.3 Steady State Flow to Cavity Wells

A cavity well is a tube well which has no strainer and draws water through the cavity formed in the aquifer just below the upper confining layer (Fig. 4.10). It does not go very deep and requires a thick clay or rock strata above the water bearing formation to form a strong and dependable roof above the cavity. The hydraulics of cavity wells under steady state conditions developed by Mishra et al (1970) is described below:

Assumptions

(i) The aquifer is confined and non-leaky.
(ii) The aquifer is homogeneous and isotropic.
(iii) The shape of the cavity is part of sphere and the thickness of the aquifer is large.
(iv) The bore of the well is blind, i.e. there is no strainer and no water enters through the walls of the well.

2.3.4 Theoretical Analysis

Since water is entering the cavity radially from all directions, the flow can be assumed to be spherical. The general form of the three-dimensional Laplace equation in spherical coordinates (r, θ, ψ) is:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \phi}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial \phi}{\partial \theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 \phi}{\partial \psi^2}=0 \tag{2.15}$$

If the depth of aquifer is large, the flow can be assumed to be radial and symmetrical to the centre and Eq. (2.15) reduces to

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \phi}{\partial r}\right)=0 \tag{2.16}$$

where, $\phi = K(P - \gamma g Z)$,

K = hydraulic conductivity

γ = density of water

P = pressure head

Z = vertical co-ordinate of the flow system

g = acceleration due to gravity

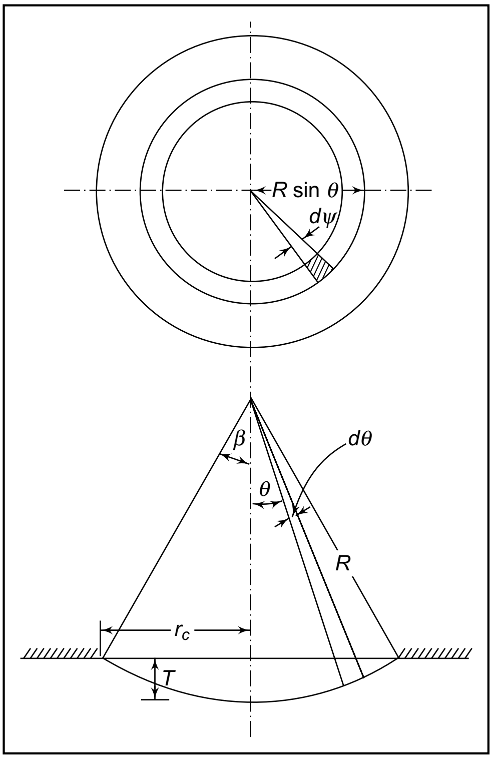

Fig. 2.7 Definition sketch of the theoretical analysis of cavity well hydraulics

After integrating Eq. (2.16),

$$\phi = \frac{C_1}{r} + C_2 \tag{2.17}$$

which indicates that ϕ varies inversely with radius r, whereas in two-dimensional radial flow it varies with the logarithm of radius.

The values of the constant of Eq. (2.17) are evaluated by using the boundary conditions $\phi = \phi_c$ at $r = r_c$, and $\phi = \phi_e$ at $r = r_e$ in which r_e is the radius of influence. The Eq. (2.17) becomes

$$\phi = \frac{(\phi_e - \phi_c)}{\left(\frac{1}{r_e} - \frac{1}{r_c}\right)}\left(\frac{1}{r} - \frac{1}{r_c}\right) + \phi_c \tag{2.18}$$

The velocity at any radius from the centre of the well (V_r) is obtained by differentiating Eq. (2.18) with respect to r

$$V_r = \frac{d\phi}{dr} = -\left[\frac{\phi_e - \phi_c}{\frac{1}{r_e} - \frac{1}{r_c}}\right]^{\frac{1}{r_c^2}} \tag{2.19}$$

The velocity through the cavity is

$$V = -\left(\frac{\phi_e - \phi_c}{\frac{1}{r_e} - \frac{1}{r_c}}\right)^{\frac{1}{r_c^2}}$$

but in practice, $r_c << r_e$, therefore

$$V = \left(\frac{\phi_e - \phi_c}{r_c}\right) \tag{2.20}$$

For a stable cavity the shape can be assumed to be part of a sphere, whose surface can be determined by taking a differential strip at any angle θ from the centre line of the well. As shown in Fig. 2.7, differential strip has vertical angle $d\theta$ and horizontal angle $d\psi$.

Integrating within limits of vertical and horizontal angles,

$$A = \int_0^{2\pi} R \sin\theta d\psi \int_0^{\beta} R\, d\theta$$

$$= \int_0^{2\pi}\int_0^{\beta} R^2 \sin\theta\, d\theta\, d\psi$$

$$= 2\pi R^2 [1 - \cos\beta]$$

Substituting the values of R and $\cos\beta$ in terms of radius of cavity r_c and depth of cavity T, respectively,

$$R = \left(\frac{r_c^2 + T^2}{2T}\right)$$

$$\cos\beta = \left(\frac{r_c^2 - T^2}{r_c^2 + T^2}\right)$$

and
$$A = 2\pi\left(\frac{r_c^2 + T^2}{2T}\right)^2\left[1 - \left(\frac{r_c^2 - T^2}{r_c^2 + T^2}\right)\right] \tag{2.21}$$

or
$$A = \pi(r_c^2 + T^2)$$

Therefore discharge through a cavity well is

$$Q = A \times V$$
$$= \pi(r_c^2 + T^2)\left(\frac{\phi_e - \phi_c}{r_c}\right)$$
$$= \pi(\phi_e - \phi_c)\left(\frac{r_c^2 + T^2}{r_c}\right) \tag{2.22}$$

In actual practice, the value of T will be very small in comparison to r_c, hence Eq. (2.22) reduces to

$$Q = \pi(\phi_e - \phi_c)\, r_c \tag{2.23}$$

which shows that, the discharge of a cavity well is proportional to radius of cavity and drawdown. For a stabilised cavity, the value of r_c is constant, and the discharge is proportional to drawdown only. The shape of cavity depends upon the size, arrangement and density of sand particles in the aquifer, confining pressure of aquifer and maximum discharge at which the cavity was developed.

2.4 UNSTEADY STATE FLOW

The flow is said to be unsteady when the flow conditions at any moment are not constant, i.e.,

$$\frac{dv}{dt} \neq 0$$

Though the hydraulic conductivity and transmissibility of confined and unconfined aquifers can easily be determined by using Thiem's steady state equations, the field conditions may be such that considerable time is required to reach steady state flow and hence aquifer properties will have to be determined under unsteady flow conditions.

2.4.1 Unsteady State Flow to Wells in Unconfined Aquifers

In unsteady state flow in an unconfined aquifer with a declining water table, dewatering of the pore space is not instantaneous but continues for some time after drawdown. The region above the water table, though unsaturated, keeps supplying water to the receding water table. Thus, the specific yield increases at a diminishing rate with the time of pumping. Hence, the saturated thickness of the unconfined aquifer is variable in magnitude. Assuming that the change in drawdown is negligible and almost constant in the dewatering area, the aquifer properties can be evaluated by the procedure adapted for unsteady state flow in confined aquifers by assuming $s' = s - s^2/2H$, m, in which s' is the drawdown component for the decrease in saturated thickness of the unconfined aquifer.

2.4.2 Unsteady State Flow to Wells in Confined Aquifers

The solution for the determination of aquifer properties under unsteady state flow conditions was developed by Theis (1935), by introducing the time factor and storage coefficient. Theis noted that, when a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of the discharge extends outward with time. The rate of decline of the head times the storage coefficient summed over the area of influence equals the discharge. Since the water must come from a reduction of storage within the aquifer, the head will continue to decline as long as the aquifer is effectively infinite. Therefore, unsteady flow exists. However, the rate of decline decreases continuously, as the area of influence expands.

Theis' equation for unsteady state flow in aquifers, derived from the analogy between the flow of ground water and conduction of heat, is based on the following assumptions which are in addition to the assumptions mentioned for the Thiem-Dupuit Eqs. (2.9) and (2.12):

1. The aquifer is confined.
2. The flow to a well is in the unsteady state, i.e. neither the drawdown difference with time is negligible nor is the hydraulic gradient constant with time.
3. The water removed from storage is discharged instantaneously with the decline of head.
4. The well diameter is very small, i.e., the storage in the well can be neglected.

The differential equation governing the unsteady state radial flow in a non-leaky confined aquifer, in polar coordinate notations is:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \tag{2.24}$$

in which,

T = transmissibility of the aquifer, m^2/s
S = storage coefficient, dimensionless
h = hydraulic head at (r, t)
r = radial distance of the piezometer from the centre of the pumped well, m
t = elapsed time after pumping is started, s

Theis (1935) obtained the solution of Eq. (2.24), based on the analogy between ground water flow and heat conduction, and for boundary conditions $h = h_o$ before pumping and $h \to h_o$ as $r \to \infty$ as pumping begins ($t > 0$), which may be written as

$$h_0 - h = \frac{Q}{4\pi T}\int_{r^2 s/4tT}^{\infty} \frac{e^{-u}}{u}\,du \tag{2.25}$$

in which

$$u = \frac{r^2 S}{4Tt} \tag{2.26}$$

and Q = constant discharge rate, m^3/s

The exponential integral is written symbolically as $W(u)$ which in this usage, is generally read 'well function of u' or 'Theis well function'.

Equation (2.25), in terms of the Theis well function, may be written as

$$s = \frac{Q}{4\pi T} W(u) \tag{2.27}$$

in which,

s = the unsteady state drawdown, m

Procedure for Determining Hydraulic Properties of Confined Aquifers

The step-by-step procedures to be followed for determining the hydraulic properties of confined aquifers is as follows:

1. A 'type curve' (Fig. 2.8) of the Theis well function is prepared on double logarithmic paper by plotting values of $W(u)$ against u, using the Table of Function (Appendix A) of Theis (1935).

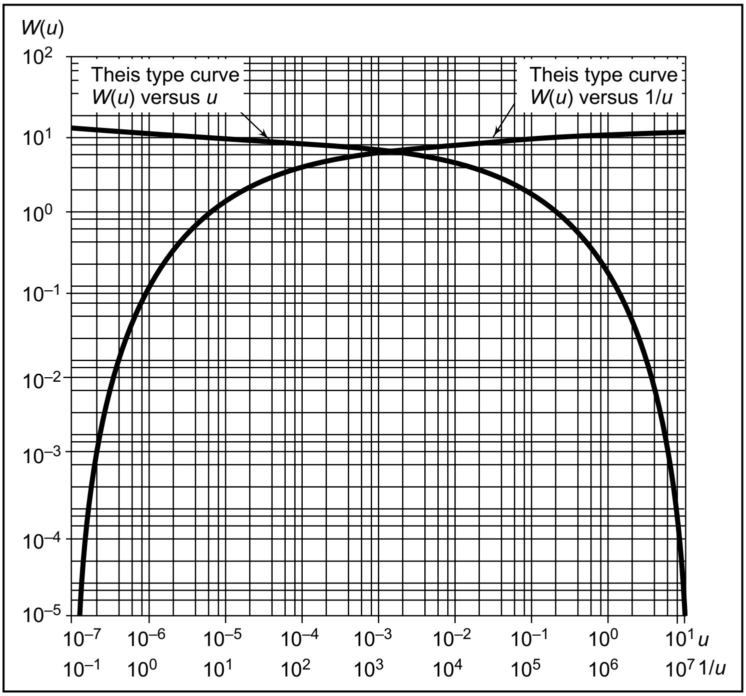

Fig. 2.8 Theis type curves for $W(u)$ versus u and $W(u)$ versus $(1/u)$

2. The values of s against t/r^2 are plotted on another double logarithmic paper on the same scale as that used for the type curve. The observed data plot is placed over the type curve. Keeping the coordinate axes of both data plot and type curve parallel, the position of best match between the data plot and type curve (Fig. 2.9) is located.
3. An arbitrary match point A on the overlapping portion of the two sheets of graph papers is selected and coordinates $W(u)$, $1/u$, s and t/r^2 for this match point are determined. The calculations are greatly simplified if the point is selected when the coordinates of the type curve $W(u) = 1$ and $1/u = 10$.

4. The value of $W(u)$, s and Q are substituted in Eq. (2.27) to obtain the value of transmissibility, T

$$T = \frac{Q}{4\pi s} W(u)$$

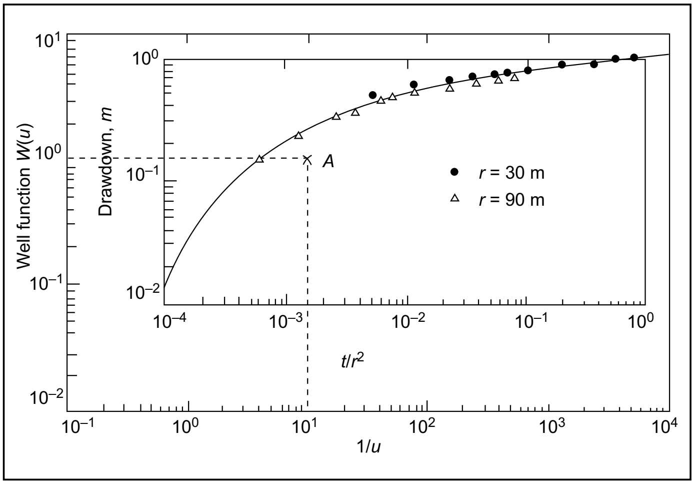

Fig. 2.9 Plot of s (drawdown) versus t/r^2 superimposed on Theis type curve $W(u)$ versus $1/u$ (Fig. 2.8), to determine confined aquifer properties (Example 2.6)

5. The value of S is calculated by substituting the values of T, t/r^2 and u in Eq. (2.26), i.e.

$$S = 4T\, u \frac{t}{r^2}$$

EXAMPLE 2.6 Calculate the hydraulic properties of an aquifer using Theis' method. The pumping test data is given in Table 2.1.

TABLE 2.1 Pumping Test Data with Constant Rate of Discharge $Q = 0.006\ m^3/min$

Elapsed time t, min	Drawdown, s m		t/r^2	
	Distance of observation well from pumped well, r			
	30 m	90 m	30 m	90 m
0	0	0	0	0
5	0.490	0.130	0.005	0.0006
10	0.680	0.207	0.011	0.0012
20	0.700	0.306	0.022	0.0024
30	0.750	0.365	0.033	0.0036
50	0.795	0.427	0.055	0.0060
60	0.820	0.450	0.066	0.0070
90	0.870	0.495	0.100	0.0110
180	0.934	0.570	0.200	0.0220
300	0.990	0.613	0.333	0.0370
480	1.050	0.700	0.533	0.0590
600	1.053	0.704	0.666	0.0740

Solution

The plots of t/r^2 versus s is superimposed on the Theis-type curve $W(u)$ versus $1/u$ (Fig. 2.9). The match point A is so chosen that the value of $W(u)$ =1 and the value of $1/u$ = 10. The value of drawdown s on A = 0.15 m and t/r^2 on $A = 1.5 \times 10^{-3}$ min/m^2. Introduction of these values in Eqs. (2.26) and (2.27) gives

$$T = \frac{0.006}{4 \times 3.14 \times 0.15} \times 1 = 0.00318 \text{ m}^2/\text{min}$$

and $$S = 4 \times 0.00318 \times \frac{1}{10} \times 1.5 \times 10^{-3} = 1.91 \times 10^{-6}$$

Cooper-Jacob Method of Solution

It was observed by Cooper and Jacob (1946) that for small values of r and large values of t, u is so small, that the series of $W(u)$ in Eq. (2.27) becomes negligible after the first two terms. Therefore, for small values of $u(u < 0.01)$ the drawdown can be approximated by using the following relationship:

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \log_e \frac{r^2 S}{4Tt}\right) \tag{2.28}$$

$$= \frac{Q}{4\pi T}\left(\log_e \frac{4Tt}{r^2 S} - 0.5772\right)$$

which reduces to

$$s = \frac{2.30\,Q}{4\pi\,T} \log_{10} \frac{2.25Tt}{r^2 S} \tag{2.29}$$

If s_1 and s_2 are the drawdowns at time t_1 and t_2, since pumping started

$$s_2 - s_1 = \frac{2.30\,Q}{4\pi\,T} \log_{10}\left(\frac{t_2}{t_1}\right) \tag{2.30}$$

If the time-drawdown data on a pumping well is plotted on a semi-log paper (Fig. 2.10) and for convenience t_1 and t_2 are chosen one log cycle apart,

$$\log_{10} \frac{t_2}{t_1} = 1, \text{ and if } s_2 - s_1 = \Delta s, \text{ then}$$

$$\Delta s = \frac{2.30\,Q}{4\pi\,T} \tag{2.31}$$

or $$T = \frac{2.30\,Q}{4\pi\,\Delta s} \tag{2.32}$$

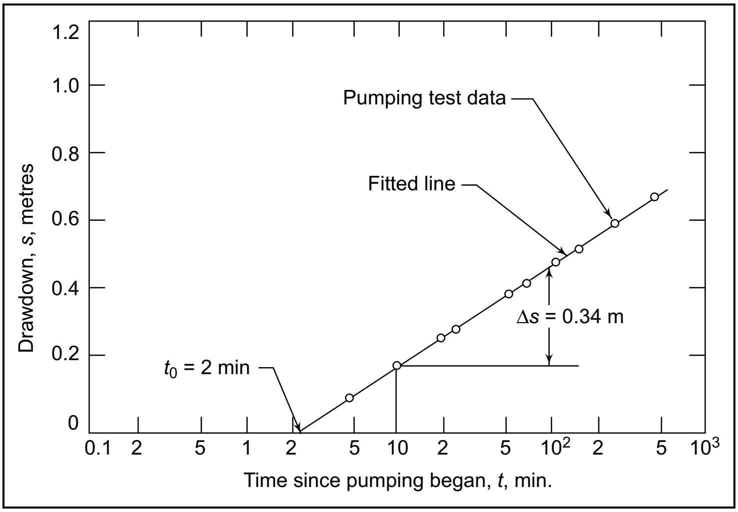

Fig. 2.10 Cooper-Jacob method for solution of non-equilibrium equation

From Eq. (2.29),

$$s = 0 \quad \text{when } \log_{10} \frac{2.25\,Tt}{r^2 S} = 0$$

i.e. when

$$\frac{2.25\,Tt}{r^2 S} = 1$$

Therefore, a plot of drawdown s versus the logarithm of t forms a straight line. Projecting this line to $s = 0$, where $t = t_0$, the time for $s = 0$ can be noted and S can be computed as

$$S = \frac{2.25\,T\,t_0}{r^2} \tag{2.33}$$

Example 2.7 Calculate the values of transmissibility and coefficient of storage, using the pumping test data of Table 2.1 for $Q = 0.006$ m^3/min. and $r = 90$ m, adopting Cooper-Jacob method.

Solution

The pumping test data of Table 2.1, s and t for $r = 90$ m are plotted on semi-log paper (Fig. 2.10). From the straight line fitted through the points, it is observed that

$$\Delta s = 0.34 \text{ m and } t_0 = 2 \text{ min.}$$

From Eq. (2.32)

$$T = \frac{2.30\,Q}{4\pi\,\Delta s}$$

$$Q = 0.006 \text{ m}^3\text{/min} = 8.64 \text{ m}^3\text{/day}$$

$$\therefore \quad T = \frac{2.30 \times 8.64}{4\pi\,(0.34)} = 4.65 \text{ m}^2\text{/day}$$

and from Eq. (2.33)

$$S = \frac{2.25\,T\,t_0}{r^2}$$

$$= \frac{2.25 \times 4.65 \times 2}{60 \times 24 \times 90 \times 90}$$

$$= 1.79 \times 10^{-6}$$

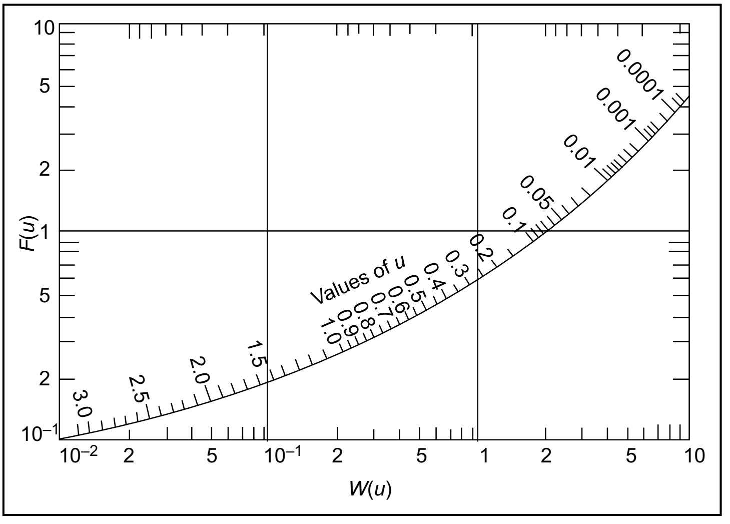

Fig. 2.11 Relationship between $F(u)$, $W(u)$ and u
Source: Chow (1952)

Chow Method of Solution

The Chow method has the advantage of avoiding curve fitting and being unrestricted in its application. The requirement of pump test data and its plotting is similar to the Cooper-Jacob method. On the plotted curve (Fig. 2.12), an arbitrary point is chosen and the coordinates of t and s are noted. A tangent to the curve at the chosen point is drawn and the drawdown difference Δs, in metres per log cycle of time is determined. The value of $F(u)$ from $F(u) = \dfrac{s}{\Delta s}$ and then the corresponding values of $W(u)$ and u are computed using Fig. 2.11. Finally the formation constants T by Eq. (2.32) and S by Eq. (2.33) are computed.

Example 2.8 Determine the formation constants, using Chow's method, from the pump test data given in Table 2.1. for $r = 90$ m and $Q = 0.006$ m^3/min (8.64 m^3/day).

Solution

The pumping test data given in Table 2.1 are plotted on semi-log paper (Fig. 2.12). Point A is selected on the curve arbitrarily where $t = 40$ min. and $s = 0.40$ m. The drawdown difference per log cycle of time is,

$\Delta s = 0.38$ m. Then $F(u) = 0.40/0.38 = 1.05$ and from Fig. 2.11

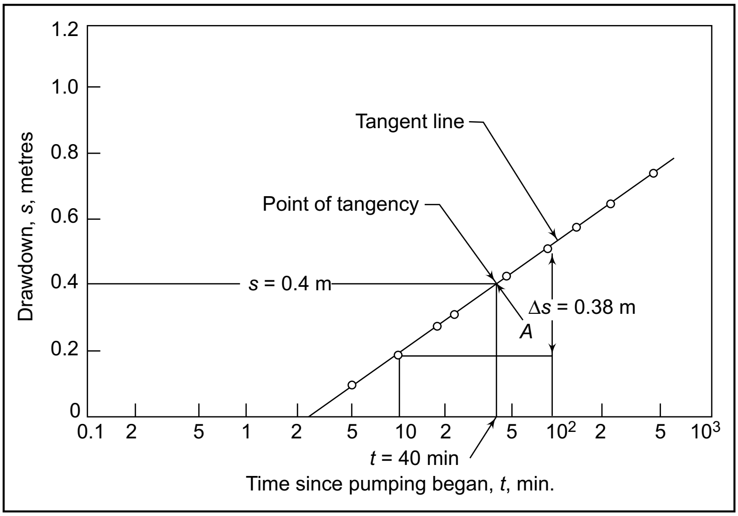

Fig. 2.12 Chow's method for solution of the non-equilibrium equation for flow in a confined aquifer

$$W(u) = 2.20, \quad u = 0.05$$

$$\therefore \qquad T = \frac{Q}{4\pi\,\Delta s}\,W(u) = \frac{8.64}{4\pi \times 0.38} \times 2.2$$

$$= 3.98 \text{ m}^2/\text{day}$$

$$S = \frac{4Ttu}{r^2} = \frac{4 \times 3.98 \times 40 \times 0.05}{24 \times 60 \times 90 \times 90}$$

$$= 2.72 \times 10^{-6}$$

Recovery Test

When the pump is stopped at the end of a pumping test, the water level in the well and in the observation wells start rising. This is referred to as the recovery of ground water level. The fall in water level (drawdown) below the original static water level (before pumping) and during the recovery period are known as residual drawdown. Figure 2.13 shows a schematic diagram of change in water level with time during and after pumping. The transmissibility of the aquifer can be calculated by analysing the residual drawdown, which will provide an independent check on pumping test results. The rate of recharge to the well during the recovery period is assumed to be constant, whereas it becomes difficult to control the pumping rate in the field. Moreover, in case of recovery test, measurements of recovery can also be made in the well in the absence of an observation well.

The residual drawdown s' can be calculated as follows (Theis, 1935):

$$s' = \frac{Q}{4\pi T}\,[W(u) - W(u')] \tag{2.34}$$

where,

$$su = \frac{r^2\,S}{4T\,t} \quad \text{and} \quad u' = \frac{r^2\,S}{4T\,t'} \tag{2.35}$$

Figure 2.13 defines *t* and *t*′. For small value of *r* and large values of *t*′, Eq. 2.34 can be approximated as

$$s' = \frac{2.30\,Q}{4\pi\,T}\log\frac{t}{t'} \tag{2.36}$$

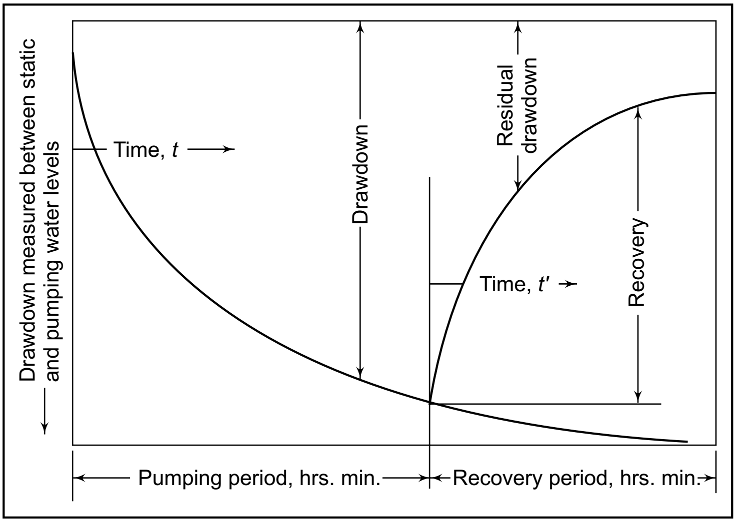

Fig. 2.13 Definition sketch illustrating the drawdown and recovery curves in an observation well near a pumping well

The residual drawdown *s*′ versus $\frac{t}{t'}$ are plotted on a semi-logarithmic paper. The slope of the straight line so plotted equals 2.30 $Q/4\pi T$, so that for $\Delta s'$, the residual drawdown per log cycle of *t*/*t*′, the transmissibility becomes

$$T = \frac{2.30\,Q}{4\pi\,\Delta s'} \tag{2.37}$$

The recovery test method cannot be used to determine the comparable value of *S*.

Example 2.9 Calculate the value of transmissibility, using the recovery test data given in Table 2.2. The uniform rate of pumping may be assumed as 2000 m^3/day. The pumping was shut down after 200 min. Thereafter measurements of *s*′ and *t*′ were taken as tabulated in Table 2.2.

TABLE 2.2 Recovery Test Data to Determine Transmissibility of Aquifer (Example 2.8)

t′, min	*t*, min	*t*/*t*′	*s*′, m
1	200	200	0.80
2	202	101	0.68
3	203	68	0.60
5	205	41	0.50
7	207	29	0.45

Contd.

TABLE 2.2 (*Contd*.)

t', min	t, min	t/t'	s', m
10	210	21	0.41
15	215	14	0.39
20	220	13	0.35
30	230	8	0.30
40	240	6	0.25
60	260	4.5	0.22
80	280	3.5	0.14
100	300	3	0.14
140	340	2.4	0.13
180	380	2.1	0.10

Solution

The values of t/t' are computed as shown in Table 2.2 and then ploted versus s' on semi-log paper (Fig. 2.14). A straight line is fitted through the points.

The value of $\Delta s' = 0.38$ m

$$T = \frac{2.30\,Q}{4\pi\,\Delta s'} = \frac{2.30 \times (2000)}{4\pi \times (0.38)}$$

$$= 963.8 \text{ m}^3/\text{day}$$

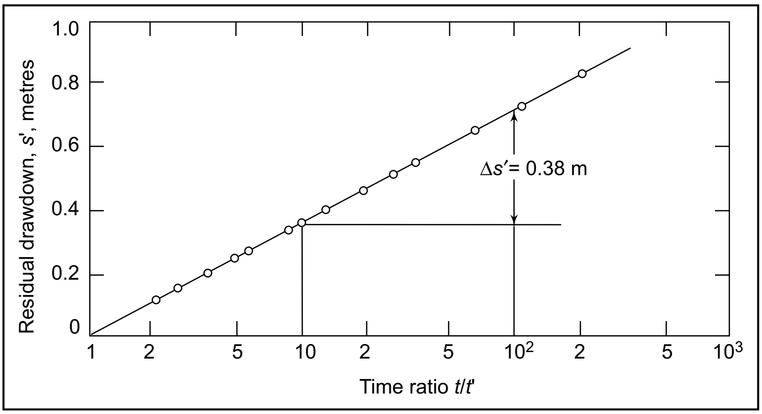

Fig. 2.14 Recovery test method for solution of the non-equilibrium equation (Example 2.9)

2.4.3 Unsteady State Flow to Cavity Wells

The solutions for drawdown behaviour around a pumped cavity well have been developed by Kanwar and Chauhan (1974) and Chauhan *et al.* (1975). These are derived from the analog between the flow of ground water and conduction of heat flow equation in spherical coordinates and are based on the following assumptions.

1. The confined aquifer is uniform, homogeneous, isotropic and has an infinite areal extent and an extensive thickness.

2. A spherical sink of infinitesimal radius r in the form of a non-penetrating well with sides impermeable and hemispherical bottom is situated at the boundary of impermeable layer and the confined aquifer.
3. The water removed from storage is discharged instantaneously with decline in head.
4. The water is pumped at a constant rate and specific storage coefficient is constant.

The following differential equation governs the unsteady state spherical flow in a non-leaky confined aquifer, in spherical coordinate notations:

$$\frac{\partial^2 h}{\partial r^2} + \frac{2\partial h}{r\partial r^2} = \frac{S_s \partial h}{K\partial t} \tag{2.38}$$

in which,

S_s = specific storage coefficient, per cm
K = hydraulic conductivity, cm/hr
t = elapsed time after pumping is started, hr
r = radial distance of piezometer from the centre of the pumped cavity well, cm

Chauhan et al. (1975) obtained the solution of Eq. (2.38) for drawdown at a distance r from pumping well at any time t as

$$s = \frac{Q}{2\pi Kr} \operatorname{erfc}(\sqrt{u}) \tag{2.39}$$

in which

Q = constant discharge, cm^3/hr
s = unsteady state drawdown, cm

$$u = \frac{r^2 S_s}{4Kt} \tag{2.40}$$

Procedure for Determining Hydraulic Properties of confined Aquifers using Cavity Wells

A type curve of the function giving relation between $\sqrt{u}$ and erfc ($\sqrt{u}$) is prepared on double logarithmic paper. The values of this function are extensively tabulated by Carslaw and Jaeger (1959) and Abramowitz and Irene (1965). The value of drawdown s and $r/\sqrt{t}$ are plotted on another double logarithmic paper on the same scale as that used for the type curve. Using a match point technique similar to that of Theis (1935) as explained in procedure for determining hydraulic properties of confined aquifers and Eq. (2.39) the value of K is obtained as

$$K = \frac{Q}{2\pi rs} \operatorname{erfc}(\sqrt{u}) \tag{2.41}$$

and S_s is calculated by substituting the values of K, $r/\sqrt{t}$ and u in Eq. (2.40) i.e.

$$S_s = \frac{4K\,t\,u}{r^2} \tag{2.42}$$

For large values of time $r/\sqrt{t} \to 0$; erfc ($\sqrt{u}$) = 1 and Eq. (2.39) reduces to

$$s = \frac{Q}{2\pi\,K\,r} \tag{2.43}$$

Thus for large values of time *t* i.e. steady state condition, knowing the value of drawdown *s*, *K* could be obtained using Eq. (2.43).

Gupta and Goel (1988) concluded that for determination of aquifer parameters using Chauhan et al. (1975) Eq. (2.39), piezometer should be installed at (*r*, 0, 0) as shown in Fig. 2.15. The distance '*r*' should be such that $r > 20\ r_c$, where r_c is radius of the hemispherical cavity. Kanwar and Chauhan (1974) solution should be used in case a piezometer fully penetrates the pumped aquifer so as to simulate average piezometric head in the aquifer.

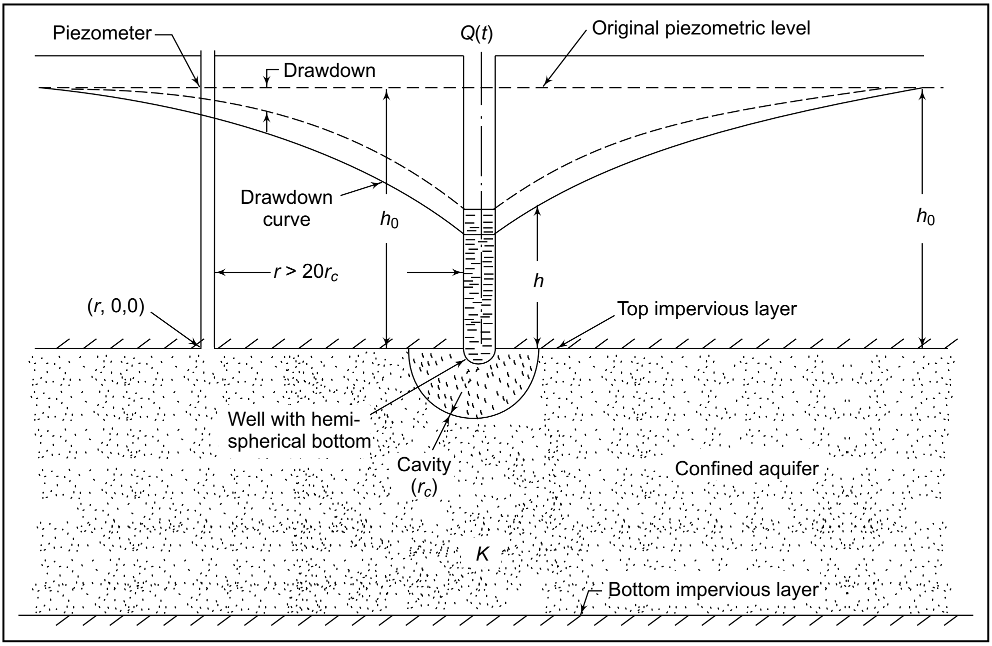

Fig. 2.15 Definition sketch illustrating unsteady state spherical flow into a cavity well in confined aquifer

Example 2.10 Calculate the values of hydraulic conductivity and specific storage coefficient using the pumping test data for cavity well given in Table 2.3; for $r = 1000$ cm and $Q = 10$ litres/sec.

TABLE 2.3 Pumping Test Data for Cavity Well with Constant Rate of Discharge $Q = 3.67 \times 10^7\ m^3/hr$ in an Observation Well at 1000 cm

t(hr)	Drawdown, s (cm)	$t^{-1/2}$ ($hr^{-1/2}$)	$rt^{-1/2}$ (cm $hr^{-1/2}$)
0.017	23.75	7.74	7740
0.033	28.00	5.50	5500
0.050	31.75	4.50	4500
0.061	35.00	3.88	3880
0.083	37.50	3.46	3460
0.166	40.00	2.44	2440
0.250	41.25	2.02	2020

Contd.

TABLE 2.3 (*Contd.*)

t(hr)	Drawdown, s (cm)	$t^{-1/2}$ ($hr^{-1/2}$)	$rt^{-1/2}$ (cm $hr^{-1/2}$)
0.330	42.50	1.77	1770
0.416	43.60	1.55	1550
0.500	43.90	1.44	1440
0.583	43.90	1.31	1310
0.666	44.25	1.23	1230
0.750	44.25	1.16	1160

Source: Kanwar *et al*. 1976

Solution

The plots of $r/\sqrt{t}$ versus s is superimposed on the type curve erfc ($\sqrt{u}$) versus $\sqrt{u}$ (Fig. 2.16). The match point is so chosen that value of erfc ($\sqrt{u}$) = 1 and value of $\sqrt{u}$ = 0.1. The value of drawdown s corresponding to this point is 49.8 cm and $r/\sqrt{t}$ = 2000 cm/hr$^{-1/2}$. Introduction of these values in Eqs. (2.41) and (2.42) give

$$K = \frac{3.67 \times 10^7 \times 1}{2 \times 3.14 \times 1000 \times 49.8} = 117 \text{ cm/hr}$$

$$S_s = \frac{4 \times 117 \times 0.01}{4000000} = 1.17 \times 10^{-6} \text{ per cm}$$

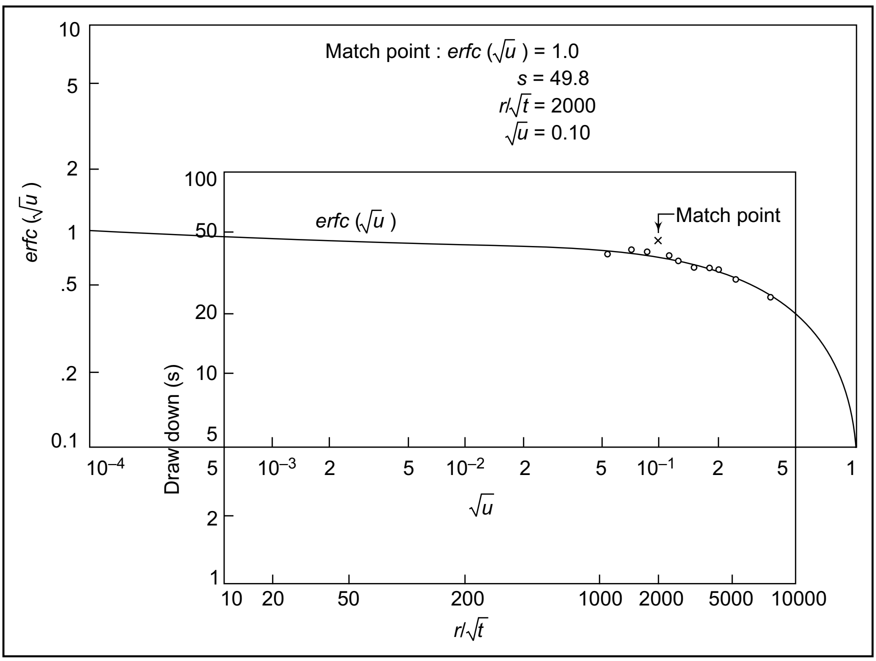

Fig. 2.16 Plot of s (drawdown) versus $r/\sqrt{t}$ superimposed on type curve erfc $\sqrt{u}$ versus $\sqrt{u}$ to determine confined aquifer parameters (Example 2.10)

2.5 PUMPING TESTS

Information on the water bearing formations and the well can be obtained by conducting pumping tests. These tests are of two types: (i) aquifer tests, and (ii) well tests. The aquifer test is carried out primarily to determine the aquifer parameters such as hydraulic conductivity, transmissibility, storage coefficient, specific yield, leakage factor and hydraulic resistance. The various methods of the determination of the aquifer parameters have been described in sections 2.3 and 2.4.

Well tests provide information about the well characteristics as well as transmissibility and storage coefficient or specific yield. It enables to determine the head loss due to flow into the screen and well. These can be determined by step drawdown test.

2.5.1 Step Drawdown Test

There are two components of head loss in ground water flow. The first is aquifer or formation loss due to laminar flow of water through the aquifer toward the well and second is well loss due to turbulent flow (Fig. 2.17). The aquifer loss is a function of both pumping rate and pumping period, whereas the well loss is a function of pumping rate alone. It represents the head loss due to resistance to flow of water as it enters the well through the screen and moves up inside the casing to the pump intake. Both the components of head loss can be expressed as

$$S_w = S_a + S_{wl} = BQ + CQ^n \tag{2.44}$$

in which, S_w = total drawdown, m

S_a = aquifer loss, m

S_{wl} = well loss, m

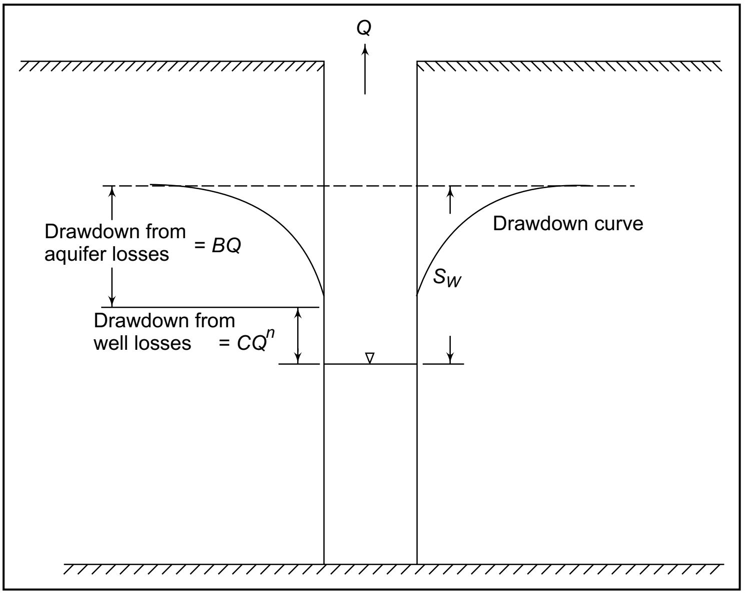

Fig. 2.17 Well and aquifer losses in a pumping well

Q = well discharge, m^3/sec
B = aquifer loss coefficient for laminar flow, usually assumed to be caused by the aquifer, sec/m^2
C = well loss coefficient for turbulent flow, usually caused by flow into the bore hole and screen, sec^2/m^5
n = severity of the turbulence

The aquifer loss and well loss components of a pumping well drawdown cannot be determined separately by collecting and analyzing the data obtained from a constant pumping rate test. These can be determined by step drawdown test. This test involves pumping a well at a series of constant rates, each larger than the previous rates. There must be at least three steps. Cooper and Jacob (1946) assumed the value of exponent n as 2, so that head loss is given by CQ^2. Thus, Eq. (2.44) becomes,

$$S_w = BQ + CQ^2 \tag{2.45}$$

Or $$S_w/Q = B + CQ$$

A plot of S_w/Q versus Q on an arithmetic graph paper gives a straight line, whose slope gives the well loss coefficient C and the intercept on the S_w/Q axis gives the aquifer loss coefficient. The value of C in equation (2.45) can also be computed by using the following equation (Cooper and Jacob, 1946).

$$C = \frac{\Delta S_2 / \Delta Q_2 - \Delta S_1 / \Delta Q_2}{\Delta Q_1 + \Delta Q_2} \tag{2.46}$$

in which,

ΔQ = increase in pumping rate at each step
ΔQ_1 = $Q_2 - Q_1$, $\Delta Q_2 = Q_3 - Q_2$
ΔS = difference in drawdown after completion of each step. Steps of any length of time may be used provided ΔS values chosen are for the same length of time in each step.

The following steps are involved in analysis of the step drawdown test data.

(i) Plot the data obtained from the pumped well on arithmetic graph paper and extend the drawdown curve for each step.
(ii) Determine the increment of drawdown between the observed water level and the extension of the preceding water level curve at equal length of time step.
(iii) Determine the value of C for different sets of two consecutive steps using Eq. (2.46). If these values of C are slightly different from each other, get an averaged out value of C.
(iv) Compute the well loss CQ^2 for each step.
(v) Knowing the well loss, discharge and drawdown S_w, determine B from Eq. (2.45).

2.5.2 Significance of Well Loss Coefficient

Equation (2.46) assumes that the well is stable and that C does not change during the step drawdown test. Small values of C denote an efficient well. In newly completed or not fully developed wells, the value of C is affected by changes in pumping rates. If value of C gets reduced substantially on increasing the pumping rate, it is probable that development has taken place during the test. If however, the value of C gets increased with higher pumping rates, it indicates clogging of the well. Thus, a step drawdown test helps to study the stability of a well.

Walton (1962) has suggested the following criteria (Table 2.4) for judging the well performance in terms of well loss coefficient *C*.

TABLE 2.4 Criteria for Judging the Well Performance in term of Well Loss Coefficient *C*

C **(sec^2/m^5)**	**Well condition**
< 1900	Properly designed and developed
1900–3800	Mild deterioration
> 3800	Severe clogging

Example 2.11 Determine the well characteristics, well loss and aquifer loss by Jacob's method for a discharge of 0.002 m^3/sec., using the step drawdawn test data given in Table 2.5.

TABLE 2.5 Step Drawdawn Test Data for Determination of Well Characteristics (Example 2.11)

Time (min)	**Depth to water level in the well (m)**	**Drawdown (m)**	**Pumping rate (m^3/sec)**	**Time (min)**	**Depth to water level in the well (m)**	**Draw-down (m)**	**Pumping rate (m^3/sec)**
0	7.50	–	–	65	9.05	1.55	0.02
1	7.95	0.45	0.01	70	9.08	1.58	0.02
2	8.00	0.50	0.01	75	9.10	1.60	0.02
3	8.02	0.52	0.01	80	9.12	1.62	0.02
5	8.05	0.55	0.01	90	9.14	1.64	0.02
10	8.10	0.60	0.01	100	9.15	1.65	0.02
15	8.17	0.63	0.01	110	9.16	1.66	0.02
20	8.14	0.64	0.01	121	9.64	2.14	0.025
25	8.15	0.65	0.01	122	9.68	2.18	0.025
30	8.15	0.65	0.01	123	9.70	2.20	0.025
40	8.16	0.66	0.01	125	9.72	2.22	0.025
50	8.17	0.67	0.01	130	9.73	2.23	0.025
60	8.17	0.67	0.01	140	9.74	2.24	0.025
61	8.98	1.48	0.02	160	9.75	2.25	0.025
62	9.01	1.51	0.02	170	9.76	2.26	0.025
63	9.03	1.53	0.02	180	9.76	2.26	0.025

Solution

The depth to water level is plotted on arithmetic graph paper in Fig. 2.18. Increments of drawdown are determined in each step for a pumping period of 60 minutes. These and the corresponding incremental discharges are:

$$\Delta S_1 = 0.67 \text{ m}, \Delta Q_1 = 0.01 - 0 = 0.01 \text{ m}^3/\text{sec}$$

$$\Delta S_2 = 0.96 \text{ m}, \Delta Q_2 = 0.02 - 0.01 = 0.01 \text{ m}^3/\text{sec}$$

$$\Delta S_3 = 0.58 \text{ m}, \Delta Q_3 = 0.025 - 0.02 = 0.005 \text{ m}^3/\text{sec}$$

$$C_1 = \frac{0.96/0.01 - 0.67/0.01}{0.01 + 0.01} = 1450 \text{ sec}^2/\text{m}^5$$

$$C_2 = \frac{0.58/0.005 - 0.96/0.01}{0.005 + 0.01} = 1334 \text{ sec}^2/\text{m}^5$$

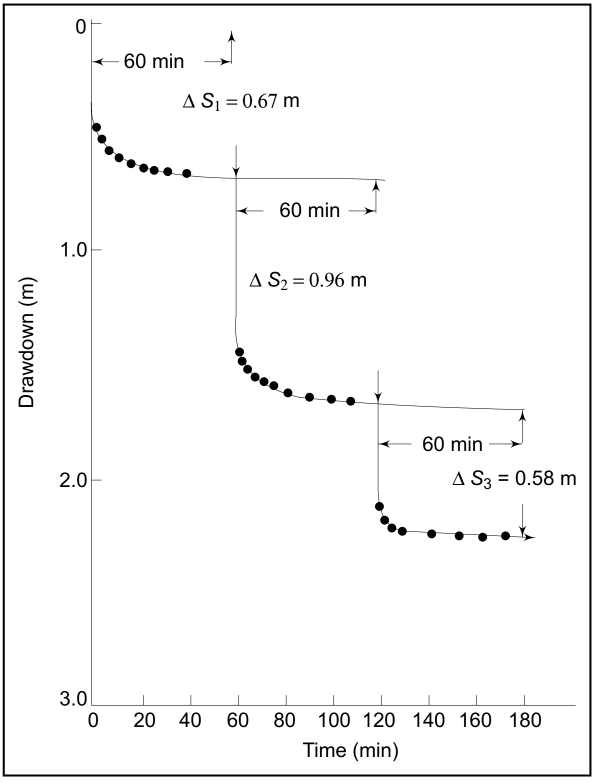

Fig. 2.18 Step drawdown test

The average value of well loss coefficient is 1392 sec^2/m^5. Hence the well loss for discharge of 0.02 m^3/sec is

$$= CQ^2 = 1392(0.02)^2 = 0.55 \text{ m}$$

$$\text{Aquifer loss} = BQ = S_w - CQ^2$$

The value of S_w for discharge of 0.02 m^3/sec is 1.66 m (Table 2.5)

$$\text{Aquifer loss} = 1.66 - 0.55$$

$$= 1.11 \text{ m}$$

Hence the well loss and aquifer loss are 33 and 67 per cent respectively.

Determination of aquifer parameters: The aquifer parameters can be determined from time drawdown data during the first step of step drawdown test using pumping test methods described earlier.

Pumping Test Procedures

The step-by-step procedure commonly adopted in conducting pumping tests is enumerated below.

Selection of the Test Site

In selecting the site of the pumping test, the following points are kept in mind:

(i) The hydro-geological conditions of the test site should not change over short distances and should be representative of the area or a large part of the area under consideration.
(ii) The site should preferably be not close to railway lines or highways with heavy traffic. Such sites may produce measurable fluctuations of the piezometric surface in the case of confined aquifers.
(iii) The pumped water does not return to the aquifer.
(iv) The gradient of the water table or piezometric surface should be low.
(v) Man-power, instruments and equipment to be used must be able to reach the site easily.
(vi) The test site should not be selected near any building or recreational area.

Observation Wells

Water level measurements during pumping tests are made in observation wells installed close to the well or at some distance away from it. The following points have to be considered for design and installation of observation wells:

(i) *Number of observation wells.* The number of observation wells depends on the amount of information desired and the degree of precision expected. Though a single observation well permits the determination of dominant hydraulic properties, a more precise value of these properties can be obtained by installing two or more observation wells at varying distances from the centre of the well. A large number of observation wells also provide information on the distance-drawdown relationship, which can be utilized for designing the spacing of the wells.
(ii) *Spacing of observation wells.* In general, observation wells should be placed neither too far from the pumped well nor too close to it. Koul (1974), reported that there was no appreciable drawdown beyond 16 m from the centre of a shallow pumped well in Delhi, for a discharge capacity of about 450 *l*/min. Krusseman and De Ridder (1990) stated that placing the observation wells about 10 to 100 m from the centre of the pumped well will provide good results in most cases. Yadav (1973) reported that the nearest observation well, for a medium-capacity shallow tube well in a semi-confined aquifer, should be placed about 1 m from the centre of the test well (Fig. 2.19). The following are the main factors influencing the spacing of observation wells:
    (a) *Type of aquifer*. In confined and semi-confined aquifers, a loss of head caused by pumping propagates faster than in an unconfined aquifer because the release of water from storage is due to the compressibility of the aquifer material and water. Hence, the nearest observation well should be placed a little farther in confined and semi-confined aquifers than in an unconfined aquifer for the same discharge rate of the test well. For the same discharge rate, the radius of influence is more in confined and semi-confined aquifers than in an unconfined aquifer. Therefore, the farthest observation well should be placed at a greater distance in confined and semi-confined aquifers than in an unconfined aquifer, to evaluate the boundary and the extent of the aquifer.

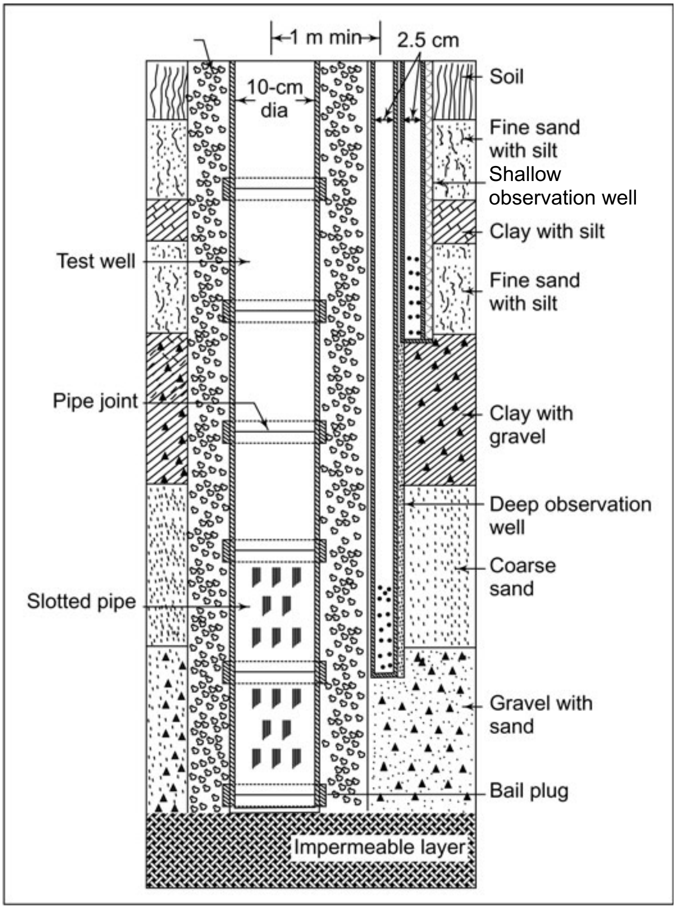

Fig. 2.19 Installation of observation wells in relation to the pumping well and the characteristics of the underground strata

(b) *Hydraulic conductivity*. When the hydraulic conductivity of the aquifer material is high, the cone of depression produced by pumping will be wide and falt, which results in a larger radius of influence as well as a greater amount of turbulence. Therefore, observation wells should be placed farther in an aquifer with a high value of hydraulic conductivity, as compared to an aquifer of lower conductivity. This applies to the observation well closest to the test well and those away from it.

(c) *Length of well screen*. The distance of the observation well adjacent to the test well is influenced by the length and depth of penetration of the well screen of the test well. The minimum distance of the observation well from the test well, in partially penetrating confined and semi-confined aquifers, should be greater than 0.5 to 2 times the thickness of the aquifer (Krusseman and De-Ridder, 1990). In case of an unconfined aquifer, a lesser distance can be used.

(d) *Stratification*. Isotropic and homogeneous aquifers seldom occur in nature. As a result of the stratification, the drawdown observed at a distance from the pumped well may vary with depth within the aquifer, because of the difference in the vertical and horizontal components of hydraulic conductivity. This effect neutralizes as the distance of the observation well from the test well increases. Although there is no fixed rule which can be employed for determining the spacing of observation wells, a range of 1 m to 100 m for the minimum and maximum distances of the observation well, with 10 to 20 m spacing, will usually be sufficient for conducting pumping tests in most cases.

(iii) *Depth of the observation well*. In a fully penetrating, confined and semi-confined aquifer, the depth of the observation well should be up to the centre of the well screen. For a partially penetrating well, the depth of the observation well should be the same as that of the test well.

In semi-confined aquifers with prompt yield and fully penetrating conditions, two observation wells should be installed at a particular location—one above the semi-pervious layer and the other reaching the middle of the well screen in the main aquifer (Fig. 2.19). When the layer below the main aquifer in a semi-confined formation is also semi-pervious, a third observation well should be installed, reaching below the bottom semi-pervious layer. By doing so, the leakage from the main aquifer or to the aquifer is accounted for.

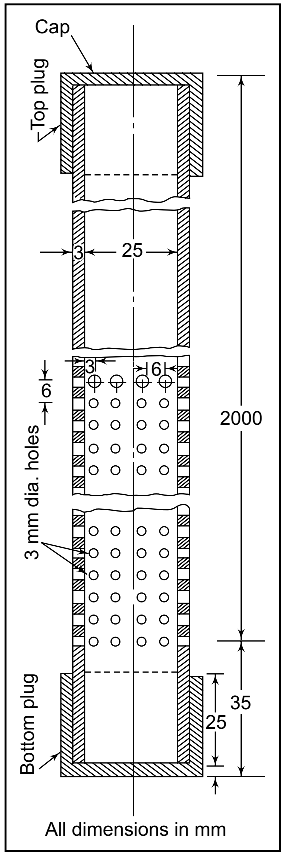

Fig. 2.20 Sectional view of a typical observation well

(iv) *Diameter of observation well*. Precise measurements of the drawdown can be made in a small diameter observation well. In practice, however, it is difficult to fabricate and install an observation well smaller than about 2.5 cm diameter. The diameter of observation wells generally range from 2.5 to 5 cm (Fig. 2.20).

(v) *Length of the perforated portion of the observation well*. The portion of the observation well casing in the aquifer should generally be perforated (Fig. 2.20). However, a shallow observation well which is installed above or below a semi-confined aquifer may be perforated only about 1 to 2 m at the bottom.

(vi) *Size of perforations of observation well*. The size of the perforation should be designed on the basis of the particle-size distribution of the strata in which it is installed and the size of drilling tool available for making the perforations. Since well development is not usually possible in an observation well, the size of the perforations should be smaller than that of the well screen in order to protect it from clogging. However, perforations of size 2 to 5 mm, covered with rope or PVC fibre, may be used in coarse formations.

(vii) *Installation of observation wells*. The observation well is placed in the hole made by a soil auger or core-drilling machine. After placing the observation well, the annular space around the screen should be filled with uniform coarse sand or gravel in order to facilitate the rapid entrance of water into it. When an observation well penetrates several aquifers or semipervious or impervious layers, the annular space against these formations is filled with fine sand or clay to prevent leakage from one layer to another.

Duration of Pumping Test

The duration of the pumping test depends on the type of aquifer, hydraulic properties of the aquifer and the method to be used for analysing pumping test data. Reliable information can be obtained if pumping continues till a nearly steady state condition is reached. This condition is obtained in about 15 to 20 hours, in a semi-confined aquifer. In a confined aquifer, the duration should be 24 to 40 hours, approximately. However, it is not always necessary to wait till steady state condition is reached.

2.6 WELL INTERFERENCE

Mutual interference of wells refers to the phenomenon in which the drawdown of wells interfering with each other increases and their capacity decreases. If the spacing between the wells is not adequate (Appendix D), the discharge of both wells will be reduced. The drawdown at any point in the area of influence is equal to the sum of the drawdown caused by each well individually (Fig. 2.21).

Thus, $$S_w = S_{w1} + Sw_2 + \cdots + S_{wn} \qquad (2.47)$$

where, S_w is the total drawdown at a given point and S_{w1}, Sw_2, ..., S_{wn} are drawdowns caused by discharge of wells 1, 2, ..., n, respectively at that point.

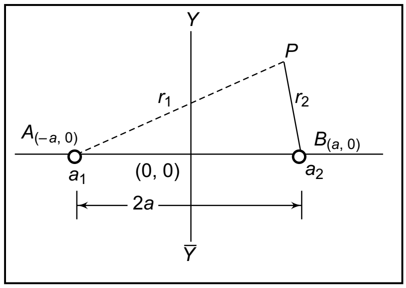

Fig. 2.21 Two wells in a straight line

Interference of Wells in Confined Aquifers

For steady state conditions, the total drawdown is given by

$$S_w = \sum_{i=1}^{n} \frac{Q_i}{2\pi Kb} \ln \frac{R_i}{r_i} \qquad (2.48)$$

where, S_w = total drawdown at a given point in the area of influence

R_i = distance from the ith well to a point at which the drawdown becomes negligible

r_i = distance from the ith well to the given point

Let two wells of equal radii be located at A and B, with equal drawdown, and the spacing between them be 2a (Fig. 2.21). Let r_1 and r_2 be the distances of any given point P from the centres of wells A and B, respectively. The drawdown at a point P, due to wells A and B, can be written as

$$s_w = \frac{Q_1}{2\pi Kb} \ln \frac{R}{r_1} + \frac{Q_2}{2\pi Kb} \ln \frac{R}{r_2} \qquad (2.49)$$

Considering the point on the face of either well at A and B, respectively, we get

$$s_{w1} = \frac{Q_1}{2\pi Kb} \ln \frac{R}{r_w} + \frac{Q_2}{2\pi Kb} \ln \frac{R}{2a} \tag{2.50}$$

and
$$s_{w2} = \frac{Q_1}{2\pi Kb} \ln \frac{R}{2a} + \frac{Q_2}{2\pi Kb} \ln \frac{R}{r_w} \tag{2.51}$$

Taking $= S_{w1} = S_{w2}$ and $Q_1 = Q_2$

$$H - h_w = \frac{Q}{2\pi Kb} \ln \frac{R^2}{r_w \times 2a} \tag{2.52}$$

or
$$Q_1 = Q_2 = \frac{2\pi Kb(H - h_w)}{\ln \dfrac{R^2}{r_w \times 2a}} \tag{2.53}$$

Similarly, for three wells forming an equilateral triangle spaced at distance $2a$,

$$Q_1 = Q_2 = Q_3 = \frac{2\pi Kb(H - h_w)}{\ln \dfrac{R^3}{r_w \times 2a \times 2a}} \tag{2.54}$$

For three wells equally spaced at a distance of $2a$, on a straight line, the discharge of the outer wells

$$Q_1 = Q_3 = \frac{2\pi Kb(H - h_w) \ln \left(\dfrac{2a}{r_w}\right)}{\ln\left(\dfrac{R}{2a}\right) \ln\left(\dfrac{2a}{r_w}\right) + \ln\left(\dfrac{2a}{2r_w}\right) \ln\left(\dfrac{R}{r_w}\right)} \tag{2.55}$$

Whereas the discharge of the middle well

$$Q_2 = \frac{2\pi Kb(H - h_w) \ln \left(\dfrac{2a}{2\, r_w}\right)}{2 \ln (R/2a) \ln (2a/r_w) + \ln (2a/2r_w) \ln (R/r_w)} \tag{2.56}$$

The above equations can be applied to unconfined aquifers by replacing H by $H^2/2$ and h_w by $h_w^2/2$.

Thus, the discharge of each of the two wells spaced at a distance of $2a$ in an unconfined aquifer is given by

$$Q_1 = Q_2 = \frac{\pi K(H^2 - h_w^2)}{\ln \dfrac{R^2}{r_w \times 2a}} \tag{2.57}$$

Example 2.12 Three wells, each having a diameter of 10 cm, are installed at the vertices of an equilateral triangle 10 m apart, in a confined aquifer. The radius of influence of each well is

500 metres, and K is 20 metres per day. The drawdown is 2 metres. The thickness of the confined aquifer is 15 metres. Find the discharge of each well, and the percentage decrease in discharge because of well interference.

Solution

The discharge of each well with interference is given by

$$Q = \frac{2\pi Kb(H - h_w)}{\ln \dfrac{R^3}{r_w \times 2a \times 2a}}$$

$$= \frac{2\pi \times 20 \times 15 \times 2}{2.303 \log_{10} \dfrac{500 \times 500 \times 500}{0.05 \times 10 \times 10}}$$

$$= 221.27 \text{ m}^3/\text{day}$$

The discharge of each well, without interference, is given by

$$Q = \frac{2\pi Kb(H - h_w)}{\ln \dfrac{R}{r_w}}$$

$$= \frac{2\pi \times 20 \times 15 \times 2}{2.303 \log_{10} \dfrac{500}{0.05}}$$

$$= 409.03 \text{ m}^3/\text{day}$$

∴ Reduction in discharge because of interference

$$= \frac{409.03 - 221.27}{409.03} \times 100$$

$$= 45.9\%$$

Water Level Measurement

An important part of a pumping test is the precise measurement of the depth to water level in the observation well and, if possible, in the pumped well. These measurements must be taken many times during the pumping test. Since the water level falls very fast from the first few minutes to the first few hours, measurements should be made as often as possible during this period. The time interval may be increased with the progress of the pumping test. Different methods of measuring water levels in pumped well and observation wells are described in Article 6.6.

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PROBLEMS

2.1. A column of sand 20 cm in length is placed in a cylindrical column of 25 cm diameter. By maintaining a constant head of 10 cm during a period of time of 10 minutes, 100 ml of water passed through the sample. Calculate the hydraulic conductivity of the sample.

Ans. Hydraulic conductivity = 0.000678 cm/sec.

2.2 A well penetrating a confined aquifer 10 m thick was tested with a uniform discharge of 1500 1/min. The steady state drawdowns measured in two observation wells, which were at 1 m and 10 m radial distances from the centre of the pumped well, were 5 m and 0.5 m, respectively. Determine the hydraulic properties of the aquifer.

Ans. Transmissibility = 0.0122 m^2/min.
Hydraulic conductivity = 0.00122 m/min.

2.3 A 15-cm diameter well at PAU Farm, penetrating an artesian aquifer, was tested with a constant discharge of 800 l/min. The drawdowns measured in three observations wells, spaced 10 m, 50 m and 100 m from the well, are given below:

Time since pumping started, min.	*r* = 10 m Drawdown, m	*r* = 50 m Drawdown, m	*r* = 100 m Drawdown, m
1	0.590	—	—
2	0.600	—	—
3	0.650	—	—
5	0.800	—	—
10	0.900	0.452	0.100
20	0.930	0.505	0.304
40	1.318	0.556	0.404
60	1.566	0.602	0.455

Determine the hydraulic properties of the aquifer using Theis' method.

Ans. $T = 0.3302$ m^2/min
$S = 198 \times 10^{-4}$

SHORT QUESTIONS

I. State True (T) or False (F).

1. The transmissibility of a confined aquifer depends upon the depth of the water table.
2. By doubling the diameter of a well, the yield is doubled.
3. Storage coefficient is the same as the specific yield for unconfined aquifer.
4. Closer the water table contour spacing higher is the gradient of ground water flow.
5. Jacob's method of evaluating aquifer parameters is applicable for small duration pumping test and large *r*.
6. The fluid flow takes place from higher to lower hydraulic potential.
7. Minimum of two observation wells are required to find out the direction of ground water flow.
8. A cone of depression in the water table is shaped like a funnel with the narrow tip of the funnel pointing upward.
9. Excessive pumping in relation to recharge can cause the water table to go down.
10. The water table is the altitude where the water level in a well will rise to when the well taps a confined aquifer.
11. The level at which the water stands in a well after pumping starts is called the static water level.
12. Transmissibility can be determined from aquifer pumping tests.
13. Coefficient of storage is the property of unconfined aquifer.
14. Specific retention is expressed in percentage.
15. Specific yield is dimensionless.
16. The hydraulic resistance is a property of confined aquifer.
17. Hydraulic resistance has dimension of time.
18. For impervious layer the value of hydraulic resistance is zero.
19. High value of leakage factor indicate a greater resistance of the semi-pervious strata to flow, as compared to the resistance of the aquifer itself.
20. Leakage factor is defined as square root of the product of transmissibility of the aquifer and hydraulic resistance of semi-pervious layer.
21. Leakage factor has the dimension of time.
22. The hydraulic gradient at water table is equal to slope of surface at that point.
23. Leakage factor and hydraulic resistance are properties of unconfined aquifer.
24. A cavity well requires a thick clay or rock strata above the water bearing formation.
25. In cavity well water enters from all sides of well screen.
26. In fully penetrating wells the flow is radial.
27. In cavity well the flow is assumed to be spherical.
28. In unsteady state flow the flow conditions are independent of time.
29. Theis solution is based on the analogy between ground water flow and heat conduction.
30. The fall in water level below the original static water level and during the recovery period is known as residual drawdown.

31. The recovery test can be used to determine the value of specific yield.
32. Aquifer test can provide information about the well characteristics.
33. The pumping water level in a well is independent of rate of pumping.
34. In unconfined aquifer, the farthest observation well should be placed at a greater distance than in an confined aquifer, to evaluate the boundary and the extent of aquifer.
35. High hydraulic conductivity of the aquifer material results in a larger radius of influence.
36. For the same drawdown, the discharge in a partially penetrating well will be more than fully penetrating well.
37. If permeability remains uniform, the velocity of ground water will increase as the slope of the water table increases.
38. Filter points are also wells.
39. Ground water has a tendency to move toward areas of low reduced pressure.
40. The size of the perforations on observation wells should be greater than that of the well screen.

Ans: True 3, 4, 6, 9, 12, 14, 15, 17, 19, 20, 24, 26, 27, 29, 30, 35, 37, 38, 39.

II. Select the correct answer.

1. The part of water that is retained in the unit volume of aquifer when it is freely drained is called
   (a) specific yield (b) specific storage
   (c) specific retention (d) porosity
2. The quantity of water that a unit volume of aquifer will yield when drained by gravity is called
   (a) specific storage (b) specific capacity
   (c) specific release (d) specific yield
3. Hydraulic resistance is a property of a
   (a) semi-pervious layer (b) confined aquifer
   (c) unconfined aquifer (d) artesian aquifer
4. Specific yield is the property of
   (a) confined aquifer (b) unconfined aquifer
   (c) leaky-confined aquifer (d) artesian aquifer
5. Darcy's law for ground water flow through porous media states that velocity of flow is proportional to
   (a) the difference in hydraulic heads (b) the distance along the flow path
   (c) the reciprocal of hydraulic gradient (d) the logarithm of hydraulic gradient
6. The radius of influence is the horizontal distance between the centre of the pumped well and
   (a) the first observation well (b) the last observation well
   (c) a point on the cone of depression of zero drawdown
   (d) a point on the cone of depression of maximum drawdown
7. If the porosity of a sample from an aquifer is 30 per cent, the specific yield will be
   (a) less than 0.30 (b) equal to 0.30
   (c) greater than 0.30 (d) difficult to predict
8. The equation for steady radial flow to a well was first developed by
   (a) Darcy (b) Theim
   (c) Theis (d) Jacob

9. The dimension of leakage factor (B) of the aquifer is
   (a) L/T (b) L
   (c) T (d) LT
10. The dimension of hydraulic resistance (c) of the aquifer is
   (a) L/T (b) L
   (c) T (d) LT
11. A high value of leakage factor indicates
   (a) a greater resistance of the semi-confined layer to flow
   (b) a small resistance of the semi-confined layer to flow
   (c) semi-confined layer is an aquifer
   (d) resistance of the semi-confined layer to flow is less as compared to resistance of the aquifer itself
12. A cavity well is tube well which has
   (a) a strainer (b) no strainer
   (c) slotted pipe and gravel pack (d) a brass screen
13. In Theis type curve method, the aquifer properties of confined aquifer are determined by selecting a match point on overlapping portion of plot of
   (a) s versus r/t and Theis type curve $W(u)$ versus $1/u$
   (b) s versus t/r and Theis type curve $W(u)$ versus u
   (c) s versus t/r and Theis type curve $W(u)$ versus $1/u$
   (d) $1/s$ versus t/r and Theis type curve $W(u)$ versus $1/u$
14. Theis equation is used to determine aquifer parameters for
   (a) unconfined aquifer (b) confined aquifer
   (c) multilayered aquifer (d) leaky-confined aquifer
15. The Dupuit assumption for unconfined flow state the velocity of flow is proportional to the
   (a) sine of hydraulic gradient (b) cosine of hydraulic gradient
   (c) tangent of hydraulic gradient (c) cotangent of hydraulic gradient
16. For a given discharge rate, the radius of influence is more in
   (a) unconfined aquifer (b) confined aquifer
   (c) perched aquifer (d) multilayered aquifer
17. In a fully penetrating well in confined aquifer, the depth of the observation well should be up to
   (a) top of the well screen (b) centre of the well screen
   (c) bottom 2/3rd of the well screen (d) bottom of the well screen
18. When the hydraulic conductivity of the aquifer material is high, the cone of depression produced by pumping will be
   (a) narrow and flat (b) narrow and steep
   (c) wide and flat (d) wide and steep
19. The direction of ground water flow can be determined from
   (a) isobath map (b) isobar map
   (c) topographic map (d) water table depth map
20. The minimum number of observation wells required to find the direction of ground water flow is
   (a) 2 (b) 3
   (c) 4 (d) 5

21. In case of closer water level contour spacing the gradient of ground water flow is
    (a) low (b) medium
    (c) high (d) flat
22. Piezometer measure the pressure head in soil profiles which are
    (a) saturated (b) unsaturated
    (c) both (d) none of these
23. A tensiometer measures
    (a) water tension in an unconfined aquifer (b) water pressure in an unsaturated zone
    (c) water tension in a confined aquifer (d) soil moisture tension in an unsaturated zone
24. Discharge (Q) in an aquifer according to Darcy's law is calculated as
    (a) the product of hydraulic gradient $(h_1 - h_2)/l$), hydraulic conductivity (K), and area (A)
    (b) the product of hydraulic conductivity (K), area (A), and velocity (v)
    (c) the product of hydraulic gradient $(h_1 - h_2)/l$), porosity (n), and area (A)
    (d) the product of hydraulic conductivity (K), porosity (n), and permeability (k)
25. Porosity is defined as
    (a) the ratio of the volume of the solids to the volume of the rock/sediment/sample
    (b) the ratio of the volume of the solids to the volume of the voids
    (c) the ratio of volume of the voids to the volume of the rock/sediment/sample
    (d) the ratio of the volume of the voids to the volume of the solids
26. Which of the following geologic materials would make the best aquifer?
    (a) well-sorted gravel (b) poorly-sorted gravel
    (c) poorly-sorted sands (d) well-sorted sands
27. The percentage of rock's total volume that is taken up by pore space is called
    (a) permeability (b) recharge
    (c) porosity (d) aquifer
28. Permeability is a measure of rock's
    (a) density (b) water holding capacity
    (c) water transmitting capacity (d) water holding and transmitting capacity
29. The lowered region of the water table near a pumping well is called
    (a) the recharge (b) the cone of depression
    (c) the capillary fringe (d) the discharge
30. The pressure inside the well during pumping in comparison to the aquifer outside the well will be
    (a) more (b) less
    (c) equal (d) no relationship
31. Based upon the following data, the amount of ground water that will be released from storage in a ground water basin is

Area of the basin	:	1000 m^2;
Specific retention	:	5%
Change in water level	:	0.75 m
Porosity	:	25%

    (a) 0.10 ha-m (b) 0.15 ha-m
    (c) 0.1875 ha-m (d) 0.225 ha-m

32. In steady state flow, the flow conditions are
    (a) independent of space (b) independent of space and time
    (c) independent of time (d) independent of direction
33. A 'type curve' of the Theis well function is prepared on
    (a) double logarithmic paper (b) semi-logarithmic paper
    (c) probability paper (d) linear scale paper

Ans. 1 (c) 2 (d) 3 (a) 4 (b) 5 (a) 6 (c) 7 (a) 8 (b)
9 (b) 10 (c) 11 (a) 12 (b) 13 (c) 14 (d) 15 (c) 16 (b)
17 (b) 18 (c) 19 (b) 20 (b) 21 (c) 22 (a) 23 (d) 24 (a)
25 (c) 26 (a) 27 (c) 28 (c) 29 (b) 30 (b) 31 (b) 32 (c)
33 (a)

3

Open Wells

Open wells have been the major means of domestic water supply throughout the span of the recorded history of mankind. They are also used extensively in small-scale irrigation. Compared to tube wells, open wells are shallow and usually used to tap watertable aquifers. Open wells are used mainly for three purposes: (1) to extract ground water from fine grained aquifers of shallow depth, where the danger of entering small particles requires a large area of contact with the aquifer, (2) to tap ground water in hard rock areas and (3) to serve as reservoirs for ground water slowly replenishing the well. Storage of water in an open well permits its periodic extraction at a rate greater than the rate of recuperation of ground water into it.

Open wells are best suited to shallow and low-yielding aquifers.They do not require sophisticated equipment and skilled personnel for construction. They can be operated by indigenous water lifts driven by man or animal power, or low-cost mechanically operated centrifugal pumps. Open wells can be revitalized by deepening or providing bores at the bottom or sides. However, open wells have the following limitations.

1. Large space is required by the well structure and for dumping excavated material.
2. Construction of well is slow and laborious.
3. Open dug wells are economically unsuitable for tapping deep aquifers, as the cost of construction becomes excessive as the depth of the well increases (Deeper aquifers could, however, be tapped by resorting to dug-cum-bore wells).
4. They are susceptible to contamination or pollution from surface sources, unless properly protected.
5. Due to shallow water table there are large water level fluctuations and there is possibility of the well drying up, especially during drought periods.

Depending upon the nature of the ground water formation to be tapped, open wells are classified as: (i) open wells in unconsolidated formations, and (ii) open wells in hard-rock formations.

Open wells may be either circular or rectangular in cross-section. The circular shape is preferred in alluvial and other porous formations because of its greater structural strength and convenience in well sinking. However, open wells in hard-rock formations are usually rectangular in shape. For the same area of cross-section, the perimeter of a rectangular well is more, and hence the area exposed to seepage of water into it from fractures and fissures, are substantially higher in a rectangular well than in a circular one.

Wells sunk in loose or unconsolidated formations require steining (lining) or retaining walls. The lining prevents the collapse of the well hole in unconsolidated formations, supports the pump platform and stops the entry of contaminated surface water. Different masonry materials, such as stones, bricks and concrete blocks, are used as lining materials in open wells. Generally, wells are designed for the purpose of irrigation, drainage, sanitation and domestic and industrial water supply. The design of each type of well requires particular attention, taking into account its purpose. Designing a water well involves the selection of proper dimensional factors for the well structure and choice of materials to be used in its construction. Good design aims at an optimum combination of performance, long service life and reasonable cost.

The hydraulic and hydro-geological characteristics of aquifers vary greatly. Irrigation wells should be designed and constructed to take advantage of the natural conditions at a given location. Water wells are usually designed to obtain the highest yield available from the aquifer and the highest efficiency in terms of specific capacity. These factors bear directly upon operating costs. Two general principles influencing the design of both open wells and tube wells are the requirement of water and location of the well.

Water Requirement

The yield potential of a well is evaluated on the basis of hydrological conditions of the area—rainfall, runoff and recharge. When the yield potential of an area is not a limiting factor, a properly designed irrigation well should provide the required quantity of water to irrigate the entire area owned by the farmer. In water-supply wells, it should provide the quantity of water required for domestic or industrial units. In case of irrigation wells, the requirements of water will depend on the types of crops and their water requirements, the area of land to be irrigated, and the cropping pattern. The contribution of rainfall during crop-growing periods and the chance of occurrence of drought should also be considered while designing the well.

When the yield potential of a well is more than the requirement of water for the farm under the control of the well owner, it is always economical to sell the additional yield to neighbouring farmers, rather than limiting the capacity of the well, to the requirement of a small or medium-sized holding. Often, it is not economical to have separate wells for individual small holdings. In an area with predominantly small holdings, it is desirable that high-discharge irrigation wells are owned jointly by a group of farmers under a suitable cooperative set-up, or by an appropriate state agency. Alternatively, wells could be owned by individuals, on a commercial basis who sell the water to different users. In water-supply schemes, the discharge of a well could be distributed to a large number of users. Additional potential, if any, could be used for agricultural or community programmes.

3.1 OPEN WELLS IN UNCONSOLIDATED FORMATIONS

Open wells in unconsolidated formations (usually alluvial) are dug down to about 7 to 10 m below the water table in the dry season. They are usually circular in shape, the diameter varying from 2 to 5 m. The wells, in general, derive their water from unconfined aquifers.

3.1.1 Types of Open Wells

(i) Unlined wells
(ii) Wells with pervious lining
(iii) Wells with impervious lining
(iv) Dug-cum-bore wells

Unlined Wells

Well dug for purely temporary purposes are not usually protected by lining, since this increases the cost of construction, which cannot be justified in a particular situation (Fig. 3.1). As the sides of the wells are not protected, it is essential that the sub-soil is compact enough to stand vertically under natural conditions. The water table should not be lower than about 4 m below the ground level. To ensure stability, the depths of unlined wells is limited to about 6.5 m.

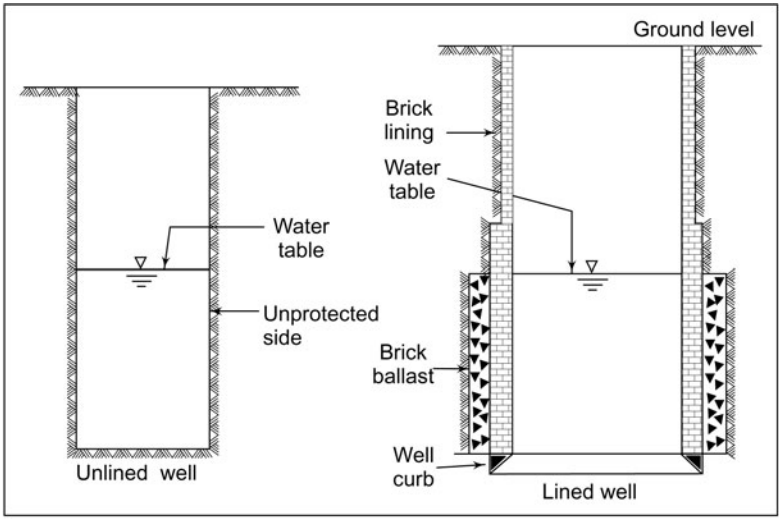

Fig. 3.1 Open wells—unlined and lined with pervious lining

Wells with Pervious Lining

This type of wells are usually lined with dry bricks or stone masonry. Water flows from the surrounding aquifer into the wells through the sides of the well. Pervious lining is suitable when the water-bearing formation consists of gravel or coarse sand deposits. When the formation consists of layers of fine sand, the sand particles escape along with water into the well, through the pervious lining. As a result, a hollow space or cavity is formed behind the well lining, thus endangering the structural stability of the well. The annular hollow space around the well lining will be self-sealing in loose formations but, in cohesive materials, it must be filled with brick or stone ballast. The ballast is about 2 cm in size and packed behind the lining. It should extend at least upto the static water table. Figure 3.1 shows the typical cross-section of a well with pervious lining. The following procedure can be adopted to construct wells with stable pervious linings:

A 30 cm deep lining is constructed over the well curb, in cement mortar. The remaining part of the well lining, upto the static water level, is laid dry without mortar, with the exception that 30 cm strips of lining in cement mortar are provided after every 1.25 m of dry lining. Above the water table, the lining is constructed in cement mortar up to the top. When the rate of withdrawal of water from the well is not excessive, and where aquifer and subsoil conditions permit, pervious lining is economical and lasting.

Wells with Impervious Lining

Open wells with permanent masonry lining, laid in cement mortar, are commonly used in alluvial formations (Fig. 3.2). Once constructed, they form a permanent structure for tapping water, as long as ground water conditions remain favourable. Though wells with impervious linings are usually deeper than the two types described earlier, their depths generally do not exceed 30 m as, beyond that, the cost becomes excessive and the well tends to be uneconomical. Such linings are provided with weep holes for the lateral entry of water.

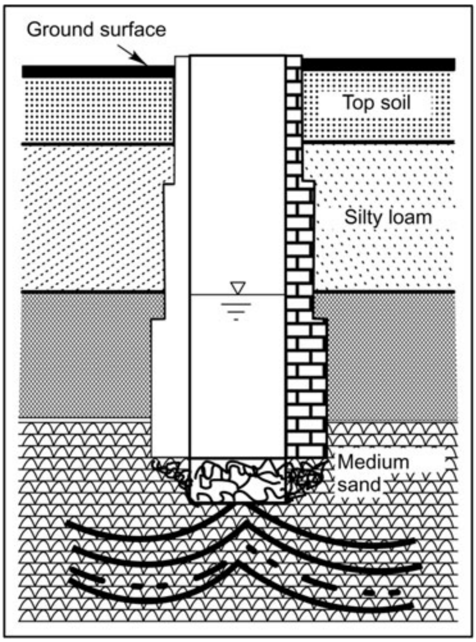

Fig. 3.2 Open well with masonry lining and inverted filter at bottom

Wells with Reinforced Cement Concrete (RCC) linings are also sometimes used, especially for higher depths. In some shallow watertable regions, RCC collar wells, sometimes referred to as ring wells are used, though mainly for domestic water supply.

Dug-cum-Bore Wells

Dug wells are sometimes provided with vertical bores at their bottom, to augment their yields. Such wells are referred to as dug-cum-bore wells. Boring consists essentially of drilling small diameter holes of sizes ranging from 7.5 to 15 cm in diameter, through the bottom of the well, and extending them upto or into the water-bearing formation lying underneath the bottom of the dug well. In unconsolidated formations there is usually only one hole, which is bored at or near the centre of the well bottom. In hard-rock areas, however, the number of holes may range from 1 to 6 depending on the nature of the rock and the size of the well.

The bore in open wells may be of two types, according to whether they tap the water-bearing medium through a cavity formed below a hard impermeable strata or through strainers or screens provided opposite the water-bearing stratum/strata (Figs. 3.3 and 3.4). In the first type, the bore extends to the top of the water bearing formation, where a cavity is formed. In the second type, well screens are laid opposite the water bearing formations and blind pipes provided opposite the non-water bearing strata. The first type i.e. a cavity bore, is cheaper but feasible only for shallow artesian aquifers lying beneath the bottom of a dug well.

Dug-cum-bore wells are hydraulically superior to ordinary dug wells. However, their success will depend on the availability of confined aquifers at reasonable depths below the dug section of the well. If a dug-cum-bore well is operated by a pumpset and the suction pipe of the pump is installed on the bored section itself, the well practically becomes a tube well. However, in such wells, the flow of ground water from the upper unconfined aquifer into the well is restricted. The well steining then serves the purpose of a pump house only. In such a situation, the construction of a regular tube well will be more economical than a dug-cum-bore well. The only advantage, however, is that it permits a phased development of the well structure.

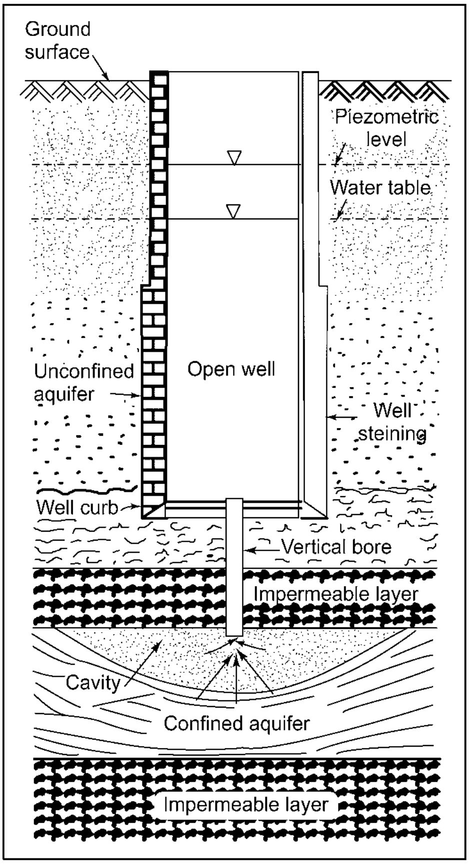

Fig. 3.3 Sectional view of an open well with a bore at the bottom ending in a cavity

3.1.2 Design of Open Wells

A properly designed open well supplies water at the required rate and remains relatively trouble-free in operation for a long period of time. The design of an open well includes the selection of its diameter and depth and the design of the well lining, its thickness and reinforcement and the design of the well curb.

Diameter of Well

Open wells in unconsolidated formations are circular in cross-section. The diameter of the well should be selected on the basis of a compromise between economical and practical considerations. It has been observed in case of masonry wells, that diameter is the main factor influencing the cost of construction.

From the point of view of the yield of a well, its diameter is decided on the basis of the concept of specific yield. Specific yield is defined as the volume of water released or stored per unit surface area of the aquifer, per unit change in the component of head, normal to that surface.

Specific yield is determined by the following relationship:

$$K' = 2.303\,(A/T')\,\log\,(H_1/H_2) \qquad (3.1)$$

where, K' = specific yield of a well, m^3/hr under a depression head of 1 m

A = cross-sectional area of the well, m^2

H_1 = difference between the water level in the well at the time of stoppage of pumping and the static water level, m

H_2 = difference of water level in the well at time T' after stoppage of pumping and the static water level, m

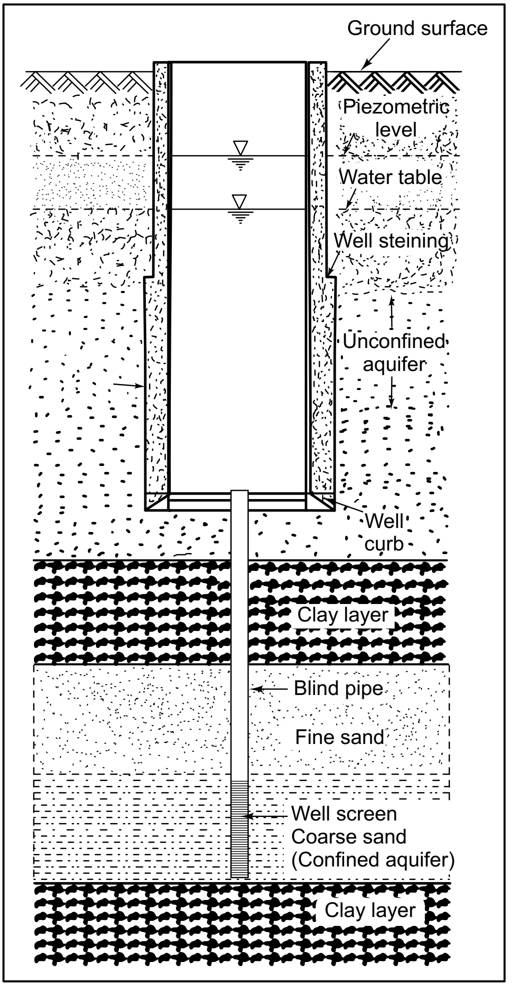

Fig. 3.4 Vertical boring provided with screen/strainer to augment the yield of an open well

Eq. (3.1) is derived as follows:

Referring to Fig. 3.5, let the discharge of an open well be proportional to the depression head H, i.e.,

$$Q \propto H$$

or

$$Q = K' H \qquad (3.2)$$

where, K' = proportionality constant, which is the same as the specific yield of the well

Let

a–a = static water level in the well, m

b–b = water level in the well when pumping is stopped, m

c–c = water level in the well at time T' after stoppage of pumping, m

d–d = water level in the well at any time t after stoppage of pumping, m

e–e = water level in the well at time $t + dt$ after stoppage of pumping, m

The quantity of water percolating into the well in a short time dt is given by

$$q = A \times dH$$

in which dH is the rise in water level in a short time dt. Further,

$$q = Q \times dt$$

$$\therefore \qquad Q \times dt = A \times dH$$

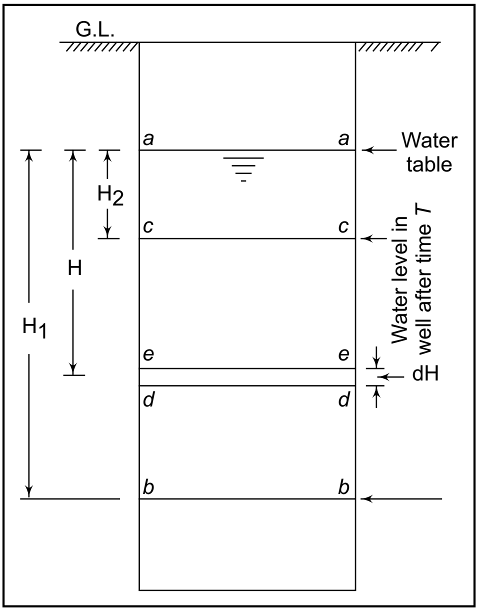

Fig. 3.5 Definition sketch to determine the diameter of an open well

Substituting the value of Q from Eq. (3.2)

$$K' \times H \times dt = A \times dH$$

Separating the variables,

$$\frac{K'}{A} dt = \frac{dH}{H} \tag{3.3}$$

Integrating Eq. (3.3) for boundary conditions,

$$H = H_1 \quad \text{at} \quad t = 0,$$

and

$$H = H_2 \quad \text{at} \quad t = T'$$

$$\int_0^{T'} \frac{K'}{A} dt = -\int_{H_1}^{H_2} \frac{dH}{H}$$

As time increases, the depression head decreases. Hence, the negative sign is used for the limits of H

$$\left(\frac{K'}{A}\right) T' = \ln \frac{H_1}{H_2}$$

or

$$2.303 \log \frac{H_1}{H_2} = \frac{K'}{A} (T')$$

∴

$$K' = 2.303\left(\frac{A}{T'}\right) \log \frac{H_1}{H_2} \tag{3.4}$$

Eq. (3.4) can also be written in the form

$$\frac{K'}{A} = \frac{2.303}{T'} \log \frac{H_1}{H_2} \tag{3.5}$$

in which,

K'/A = specific yield per unit area of the well

Specific yield may be assumed to be constant for a well when the limit of critical velocity is not exceeded. Critical velocity may be defined as the velocity of entry of water into the well at which sand particles start moving with the water. In case of open wells, the critical velocity is usually assumed as 7.5 cm/min. Table 3.1 presents the values of K'/A, suggested by Marriot (Sahasrabudhe, 1962) for various types of sub-soil formations.

TABLE 3.1 Values of Specific Yield (K'/A) for Different Subsoil Formations

Types of sub-soil	K'/A
Clay	0.25
Fine sand	0.50
Coarse sand	1.00

The discharge of a well can be predicted at the required depression head. The value of K' can then be determined as follows:

$$K' = \frac{\text{Discharge of well}}{\text{Depression head}} = \frac{Q}{H}$$

By selecting the value of K'/A from Table 3.1 for a given type of sub-soil formation and calculating the value of K', as stated above, the value of A and hence the diameter of the well may be determined. The calculated value of diameter may be modified according to the convenience of well sinking and installation of the water lifting device.

In case of masonry wells, in which flow is through the bottom of the well, the actual velocity of flow must be less than the critical velocity. After determining the well diameter, the actual velocity of flow is computed by dividing the discharge Q by the area of cross-section A. The actual velocity is checked against the critical velocity. A factor of safety of 2 to 3 is recommended for design.

EXAMPLE 3.1 A masonry well is to be constructed in a fine sand sub-soil formation. The discharge of the well is anticipated to be 15 m^3/h under a depression head of 4 m. Determine the diameter of the well.

Solution

Discharge of the well = 15 m^3/h

$$Q = K' \times H$$

Substituting, the values,

$$15 = K' \times 4$$

or $$K' = 15/4 = 3.75 \text{ m}^2/\text{h}$$

under a depression head of 1 m.

From Table 3.1, the value of K'/A for the given subsoil formation is 0.5.

$$\therefore \quad 3.75/A = 0.5$$

or

$$A = 7.5 \text{ m}^2$$

$$\therefore \quad \text{Diameter of well} = \sqrt{\frac{A \times 4}{\pi}} = \sqrt{\frac{7.5 \times 4}{\pi}} = 3.1 \text{ m}$$

Check for Critical Velocity

$$\text{Velocity of flow} = \frac{Q}{A} = \frac{15}{7.5} = 2\text{m/h}, \quad \text{or} \quad 3.33 \text{ cm/min}$$

Assuming a factor of safety of 2, it works out to be 6.67 cm/min, which is less than the permissible critical velocity of 7.5 cm/min. Hence, the design is safe.

Depth of Well

The selection of well depth will depend upon the thickness of the water bearing formation, the depth of water table below the ground surface and anticipated drawdown in the well and the storage depth while the well is in operation. The drawdown is usually taken as 4 to 6 m, when a horizontal centrifugal pump is used to lift water. The value of storage depth usually adopted is 2 m. The approximate depth of the well will, therefore, be the sum of the depth of water table below ground surface, drawdown, and storage depth.

Thickness of Well Lining

Well lining (steining) is an earth-retaining structure which supports the sides of the open well against cave-in. The steining should be so designed that it can sustain the lateral earth pressure. There is an internal pressure of water inside the well, which reduces the effect of external pressure. The rise and fall of water level in the well results in changes in internal and external pressures. The worst case is when the open well is dry, i.e. when there is no internal pressure. The well lining should be safe against this condition. Thus, a well lining should be designed as a special case of a thick cylinder with external pressure only.

Hence, considering the well as a special case of a thick cylinder (Fig. 3.6), the principal stresses developed are hoop stress and radial stress. As per Lame's solution of principal stresses (Farad et al., 1952), the hoop and radial stresses developed in a well may be expressed as follows:

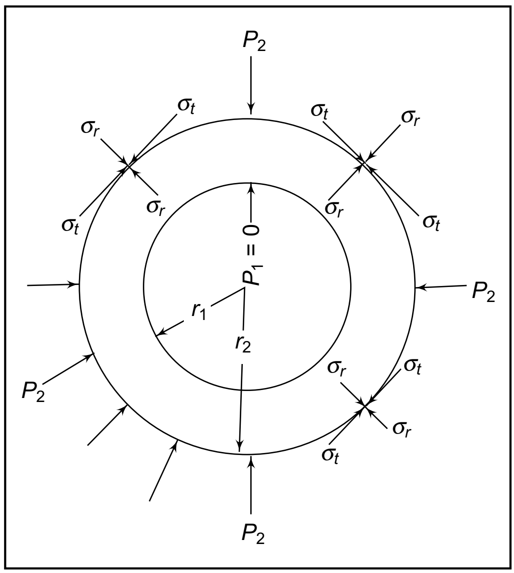

Fig. 3.6 Stresses acting on a thick cylinder subjected to external pressure only

$$\text{Hoop stress,} \quad \sigma t_{\max} = \frac{2P\, r_2^2}{r_2^2 - r_1^2} \tag{3.6}$$

$$\text{Radial stress,} \quad \sigma r_{\max} = \frac{P\, r_2^2}{r_2^2 - r_1^2} \tag{3.7}$$

in which,

r_2 = external radius of the well, cm

r_1 = internal radius of the well, cm

P = Earth pressure, kg/cm^2

$$= WH\,\frac{(1 - \sin\phi)}{(1 + \sin\phi)} \tag{3.8}$$

in which,

W = specific weight of soil, kg/cm^3

ϕ = angle of repose of the soil, degrees

H = depth of well, cm

Both hoop stress and radial stress developed in a well are principal stresses and compressive in nature. The hoop stress developed is the maximum and is twice the radial stress. Hence, it is considered for the purpose of design.

As the lateral pressure from the sides will increase with the depth of the well, it will be economical to provide different thicknesses of steining at different depth intervals. The well may be considered in sections of 3 to 5 m depths. In actual practice, however, the variable-thickness approach is used for dug wells, only when the masonry work is done after excavating the well. For sunk wells, however, the same thickness is generally adopted for the whole depth to prevent disjointing during sinking. In the latter case, the thickness is calculated, based on the stresses acting at the bottom of the well. The procedure is illustrated in Example 3.2.

EXAMPLE 3.2 Design the thickness of the brick lining of an open well having a diameter of 2 m and a depth of 20 m. The angle of respose of the soil is 25° and the specific weight of soil is 0.0016 kg/cm^3.

Solution

The design may be based on variable thickness with a depth interval of 5 m.

(a) Steining thickness for depth of 0 to 5 m from the ground surface:

$$P = WH\left[\frac{1 - \sin\phi}{1 + \sin\phi}\right]$$

$$= 0.0016 \times 500 \times \frac{(1 - \sin 25°)}{(1 + \sin 25°)}$$

$$= 0.0016 \times 500 \times \frac{(1 - 0.423)}{(1 + 0.423)} = 0.324 \text{ kg/cm}^2$$

For first-class brick masonry with 1 : 3 cement mortar, the safe compressive stress is 15 kg/cm^2.

Substituting the value of P and r_1 in Eq. (3.6),

$$15 = \frac{2 \times 0.324\, r_2^2}{r_2^2 - (100)^2}$$

$$15\, r_2^2 - 15 \times (100)^2 = 0.648\, r_2^2$$

$$r_2^2 = 100\ \sqrt{15/14.352}$$

$$= 102 \text{ cm}$$

∴ Steining thickness = 102 – 100 = 2 cm

Assuming a factor of safety of 3, the required thickness is 6 cm. However, in a brick-lined well, the minimum thickness should be 23 cm, which is the length of one brick.

Check for bearing load:

Considering a unit width of 1 cm radially, the unit weight of masonry = 0.0023 kg/cm^2

Total weight of masonry = 23 × 500 × 1 × 0.0023 = 26.45 kg

Bearing area = 23 × 1 = 23 cm^2

∴ Bearing load = 26.45/23.00 = 1.15 kg/cm^2

Therefore, the design is safe against bearing, as the bearing load is far less than the safe compressive stress of masonry which is 15 kg/cm^2 with 1 : 3 cement mortar.

(b) Steining thickness for 5 to 10 m depth from ground level:

$$r_1 = 100 \text{ cm, depth} = 10 \text{ m}$$

$$P = WH \left[\frac{1 - \sin 25°}{1 + \sin 25°}\right]$$

$$= 0.0016 \times 1000\ \frac{(1 - 0.423)}{(1 + 0.423)}$$

$$= 0.648 \text{ kg/cm}^2$$

∴ $$15 = \frac{2 \times 0.648\, r_2^2}{r_2^2 - (100)^2}$$

$$r_2 = 100\ \sqrt{15/13.704}$$

$$= 105 \text{ cm}$$

∴ Steining thickness = 105 – 100 = 5 cm

Assuming a factor of safety of 3, the thickness is 15 cm. Adopt 23 cm to have a one-brick masonry.

Check for bearing load:

$$\text{Bearing load} = \frac{23 \times 1000 \times 1 \times 0.0023}{23}$$

$$= 2.30 \text{ kg/cm}^2$$

Since it is less than 15 kg/cm^2 the design is safe against bearing load.

(c) Steining thickness from 10 to 15 m below ground surface:

$$P = WH\left[\frac{1-\sin 25°}{1+\sin 25°}\right]$$

$$= 0.0016 \times 1500 \times \frac{(1-0.423)}{(1+0.423)}$$

$$= 0.972 \text{ kg/cm}^2$$

$$\therefore \quad 15 = \frac{1.944\, r_2^2}{r_2^2 - (100)^2}$$

$$\therefore \quad r_2 = 100\sqrt{15/13.056}$$

$$= 107 \text{ cm}$$

$\therefore$ Thickness of steining = 7 cm

Assuming a factor of safety of 3, it works out to be 21 cm. Hence, 23 cm is adopted to provide a one-brick masonry (minimum recommended).

Check for bearing load:

$$\text{Bearing load} = \frac{23 \times 1500 \times 1 \times 0.0023}{23}$$

$$= 3.45 \text{ kg/cm}^2$$

Since it is less than 15 kg/cm^2, the design is safe against bearing load.

(d) Steining thickness from 15 to 20 m:

$$P = WH\left[\frac{1-\sin 25°}{1+\sin 25°}\right]$$

$$= 0.0016 \times 2000 \times \frac{(1-0.423)}{(1+0.423)}$$

$$= 1.296 \text{ kg/cm}^2$$

$$\therefore \quad 15 = \frac{2.592\, r_2^2}{r_2^2 - (100)^2}$$

$$\therefore \quad r_2 = 100\sqrt{\frac{15}{12.408}}$$

$$= 110 \text{ cm}$$

$\therefore$ Steining thickness = 10 cm

Assuming a factor of safety of 3, it works out to be 30 cm. Hence, 34.5 cm is adopted to have one and a half brick thickness.

Check for bearing load:

$$\text{Bearing load} = \frac{34.5 \times 2000 \times 1 \times 0.0023}{34.5} = 4.6 \text{ kg/cm}^2$$

Since it is less than 15 kg/cm^2, the design is safe against bearing load.

Therefore, in a dug well, a 23 cm thick brick masonry is to be provided from 0 to 15 m and 34.5 cm from 15 to 20 m. However, if a sunk well is constructed, it will be desirable to provide 34.5 cm thick masonry for the entire depth.

Nomograph for Design of Well Steining

The thickness of well steining worked out on the principle explained above for different depths and diameters of wells, is presented in Fig. 3.7 as a nomograph, giving the relationship between the above parameters. The required thickness of steining for the desired depths and diameters may be read from Fig. 3.7 and the same modified for a thickness equivalent to multiples of half-brick with a minimum of 23 cm. For dug wells, variable thicknesses may be provided for different depth intervals for economy in construction.

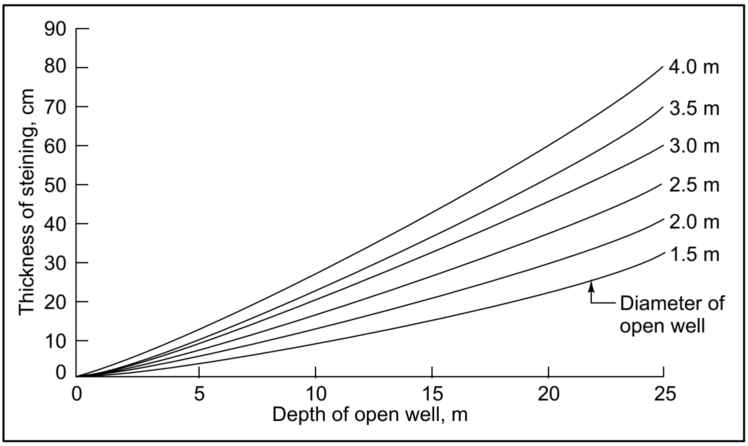

Fig. 3.7 Nomograph to determine the thickness of steining of open wells

Design of RCC Lining

Sometimes, because of non-availability of bricks or stones and to avoid excessively thick masonry lining, a reinforced cement concrete (RCC) lining may be more economical than ordinary masonry. The design procedure for the thickness of RCC lining (steining) is similar to the one adopted for masonry lining, except that the safe compressive stress for RCC of 1 : 2 : 4 mix may be taken as 40 kg/cm^2, in place of 15 kg/cm^2 for ordinary masonry. The thickness is calculated with a suitable factor of safety.

The nominal longitudinal as well as circumferential reinforcement will have to be provided. The longitudinal (vertical) reinforcement may consist of 8 to 10 mm diameter mild-steel bars at a spacing 3 times the effective thickness of RCC. The vertical bars are welded or bolted with the well curb. The circumferential reinforcement may consist of 6 mm diameter rings at a spacing of 15 cm.

The construction procedure is similar to masonry wells, except that the RCC is to be laid in increments of depth, using proper forms. Setting and curing periods will have to be provided to the RCC each time.

EXAMPLE 3.3 Design an RCC lining for the open well given in Example 3.2. The unit weight of RCC may be assumed to be 0.0035 kg/cm^2. Uniform thickness may be provided throughout the depth of the well.

Solution

Since a uniform thickness is to be provided for the entire depth, the earth pressure acting at the bottom of the well, P, is calculated.

$$P = WH \frac{(1 - \sin 25°)}{(1 + \sin 25°)}$$

$$= 0.0016 \times 2000 \times \frac{(1 - 0.423)}{(1 + 0.423)}$$

$$= 1.296 \text{ kg/cm}^2$$

The safe compressive stress for RCC of 1 : 2 : 4 mix is 40 kg/cm^2. Substituting the value of P and r_1 in Eq. (3.6),

$$40 = \frac{2 \times 1.296\, r_2^2}{r_2^2 - (100)^2}$$

$$\therefore \qquad r_2 = 100 \sqrt{\frac{40}{37.408}}$$

$$= 103.4 \text{ cm}$$

$$\therefore \qquad \text{Thickness of RCC} = 103.4 - 100 = 3.4 \text{ cm}$$

Assuming a factor of safety of 2, the actual thickness to be provided = 6.8 cm. Hence, a thickness of 7.5 cm is recommended.

Nominal Reinforcement. Assuming the effective thickness of RCC to be 6 cm, 8 mm diameter mild-steel vertical bars may be provided at a spacing of 18 cm, centre to centre. The circumferential reinforcement may consist of 6 mm diameter mild-steel rings at a spacing of 15 cm.

Check for bearing load:

$$\text{Bearing load} = \frac{7.5 \times 2000 \times 1 \times 0.0035}{7.5}$$

$$= 7.0 \text{ kg/cm}^2$$

Since it is less than 40 kg/cm^2 (safe compressive stress of RCC), the design is safe against bearing load.

Weep Holes in Well Lining

In both masonry and RCC linings an adequate number of weep holes are provided to permit the entry of water into the well. These holes are scattered throughout the section of the well lining below the static water table. In masonry lining the holes may be rectangular with an area of 80 to 120 cm^2 each. In RCC lining, the holes are circular and usually of 5 to 7.5 cm diameter.

Well Curbs

A well curb is a circular cutting edge, provided at the bottom of the steining, for sinking of open wells. The steining is constructed on the well curb, which is laid on the underground soft soil. Well curbs may be made of wood or reinforced concrete (Fig. 3.8). A wooden curb is made of hard wood. The hard wood rings are strongly joined together and secured by iron bolts to avoid the risk of its breaking during well sinking.

A reinforced cement concretre well curb (Fig. 3.8) consists of main bars (12 mm diameter) along the circumference. A nominal reinforcement in the form of triangular rings (8 mm diameter) is provided at a spacing not exceeding the lever arm (0.865 d) of the section, in which d is the effective depth of the section. The cement-concrete mix is usually 1 : 2 : 4. Vertical tie rods of about 2 cm diameter are fixed in the curb at 1 to 2 m intervals, and brought up through the centre of steining masonry. The lengths of the rods (tie rods) are 2 to 3 times their horizontal spacing. The tie rods are anchored with nuts at the top, with a circular flat iron of about 1 cm thickness and 7.5 to 15 cm width. Another plate may be used between the curb and the top ends of the rods, if necessary. The width of the well curb is 5 cm thicker than the thickness of the steining at the bottom of the well. This additional thickness would avoid any contact between the masonry and the surrounding earth during the sinking of the well, since friction between the two can damage the masonry.

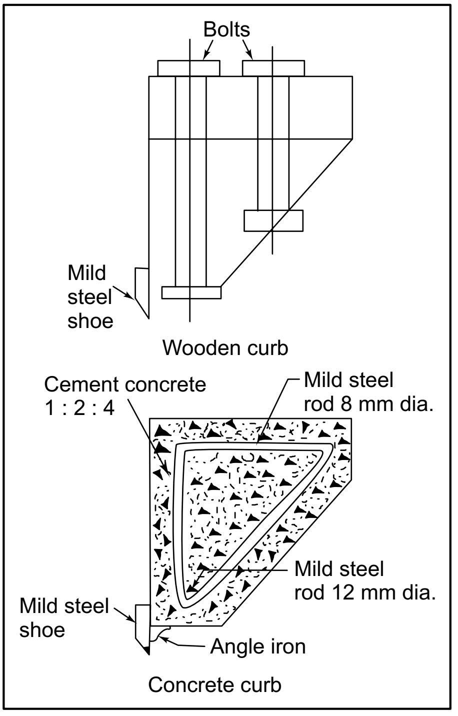

Fig. 3.8 Well curbs

Design of Well Curb

The first step in the design of a well curb is the calculation of the bending moment which the curb section has to resist. To determine the bending moment, it is assumed that 1/3 of the portion below the well curb is hollow and thus not supported by the soil underneath. The area of steel reinforcement to be provided shall be based on the bending moment.

The bending moment (M) may be estimated from the following relationship:

$$M = \frac{Wl^2}{10}, \ kg\text{-}cm$$

where, W = weight of masonry, considering a unit length along the circumference, kg/cm

l = length of the portion below well curb not supported by soil underneath, usually assumed as 1/3 of the mean circumference of well at the bottom, cm

The design procedure for different types of well curbs is given below:

(i) *Design of RCC well curb*

Depth of well curb d is given by the relationship

$$M = kbd^2$$

or

$$d = \sqrt{\frac{M}{kb}} \tag{3.9}$$

where, d = depth of well curb, cm

k = constant for a given concrete mix, kg/cm^2

b = width of the curb, cm

For a cement concrete mix 1 : 2 : 4, the value of k is 8.74 kg/cm^2.

Area of steel A_{st}. The area of steel required is given by

$$A_{st} = \frac{M}{\sigma_{st}\, Jd} \tag{3.10}$$

where, A_{st} = cross-sectional area of steel reinforcement, cm^2

σ_{st} = permissible bending stress in tension in steel, kg/cm^2

The value of σ_{st} for mild steel is 1400 kg/cm^2.

Number of steel bars

The number of steel bars

$$= \frac{A_{st}}{\text{Area of assumed diameter of bar}}$$

(ii) *Design of wooden well curb*

The design of the wooden well curb should be such that the bending moment induced is resisted by the curb section. The resisting bending moment of the section is equal to its section modulus Z (section modulus is defined as the ratio of the moment of inertia of the section and the distance of the extreme fibre from the neutral layer) multiplied by the permissible bending stress f'.

$$\therefore \quad M = Z \times f' \tag{3.11}$$

where, Z = section modulus = $I/y = \frac{bd^3}{12}\frac{2}{d} = \frac{bd^2}{6}$

b = width of well curb, cm

d = depth of well curb, cm

f' = permissible bending stress, kg/cm^2

The value of f' is approximately 100 kg/cm^2 for wood.

or $$\frac{bd^2}{6} \times f' = M$$

or $$d = \sqrt{\frac{6M}{f'b}} \tag{3.12}$$

Hence, the depth of the well curb can be calculated, using Eq. (3.12) for an assumed value of width b and the permissible bending stress.

Example 3.4 Design an RCC well curb for an open well with an inner diameter of 3 m and thickness of steining of 23 cm at the bottom. The load of masonry per unit length of the well curb is 70 kg/cm.

Solution

The width of a well curb is usually 5 cm more than the thickness of the steining being supported. Therefore, the assumed width of the curb is 28 cm.

Mean diameter of the well curb = 328 cm

Circumference of well curb $= \pi D = \frac{22}{7} \times 328$ cm

∴ Length of well curb for the purpose of calculating the bending moment

$$= \frac{1}{3} \times \frac{22}{7} \times 328 = 343.6 \text{ cm}$$

The bending moment, $$M = \frac{Wl^2}{10}$$

$$= \frac{70 \times 343.6^2}{10} = 8,26,427 \text{ kg-cm}$$

Effective depth of well curb, $$d = \sqrt{\frac{M}{kb}}$$

$$= \sqrt{\frac{826427}{8.74 \times 28}}$$

$$= 58.1 \text{ cm, say } 60 \text{ cm}$$

Area of steel required, $$A_{st} = \frac{M}{\sigma_{st}\, Jd}$$

$$M = 826427 \text{ kg-cm}$$

$$J = 0.865$$

$$d = 60 \text{ cm}$$

$$\therefore \quad A_{st} = \frac{826427}{1400 \times 0.865 \times 60}$$

$$= 11.37 \text{ cm}^2$$

Assuming mild steel bars, each of 12 mm diameter, the number of bars required = 10. A nominal reinforcement comprising of 8 mm dia. mild-steel bars in the form of triangular rings may be provided at a spacing not exceeding 0.865 d, i.e. $0.865 \times 60 = 51.90$ cm, say 50 cm centre to centre.

Example 3.5 Design a wooden well curb for an open well with an inner diameter of 4 m and thickness of steining 23 cm at the bottom. The load of masonry per unit length of well curb is 75 kg/cm.

Solution

Assumed width of well curb = 28 cm

Mean diameter of well curb = 428 cm

Length of well curb for the purpose of calculating the

$$\text{bending moment} = \frac{1}{3} \times \frac{22}{7} \times 428 = 448.38 \text{ cm}$$

$$M = \frac{Wl^2}{10} = \frac{75 \times 448.38^2}{10} = 15{,}07{,}835 \text{ kg-cm}$$

The depth of the wooden well curb is given by

$$d = \sqrt{\frac{M \times 6}{b \times 100}} = \sqrt{\frac{1507835 \times 6}{28 \times 100}} = 56.8 \text{ cm, say } 60 \text{ cm}$$

3.1.3 Location of Wells

While selecting the site for an open well, it is essential to consider the following points:

(i) The well site should be such that after its completion, it should be in a position to command all the surrounding area. If situated in the centre of the farm, the well gives good command. At the same time, care should be taken to see that the proposed site is on a slightly high patch of land so that water can flow by gravity. However, this is not a limiting condition, if an underground pipeline water-distribution system is used, in which case it is feasible to locate the well at a lower reach where the maximum water supply can be expected.

(ii) The well site should be such that it is not affected by floods, otherwise the well is likely to be damaged.

(iii) On sloping ground, the well is located at the foothill to tap the sub-surface flow, and never on the top of a mount which has very limited recharge area and hence the minimum potential for ground water.

(iv) Well sites downstream of percolation tanks, storage reservoirs, canals and streams are to be exploited to the extent possible. However, wells located very close to these water bodies will be a source of depletion of water, especially in case of unlined canals.

(v) A well should be sufficiently away from an adjoining well so that their radii of influence do not cross. Mutual interference between adjacent wells reduces the yield of each well (Fig. 3.9). The increase in drawdown results in increased area of mutual interference. Generally, a spacing of 75 to 100 m, according to the nature of the strata and depth of sub-soil water, is adopted to avoid interference between open wells in alluvial formations.

3.1.4 Construction of Open Wells

Open wells are usually excavated using pick-axes and shovels, or power-driven shovels of various designs. Many open wells are still constructed manually. Adopting the traditional method, one or more men start to dig, throwing out the dirt until the hole becomes deep. Then, a second man or group of men, standing at intermediate points, relay the excavated material and dump it on the ground surface, and so on, as the digging proceeds. Buckets and wheel barrows operated by suitable pulleys and lines are often used with advantage to lift the excavated material (Fig. 3.10). After ground water is struck, hand-excavated pits must be kept relatively dry by pumping. Dragline excavators using clamshell or orange-peel type buckets or simple cranes with manually loaded buckets are employed to excavate open wells (Fig. 3.11). Orange-peel buckets can excavate under water, unassisted, as long as there is no cave-in.

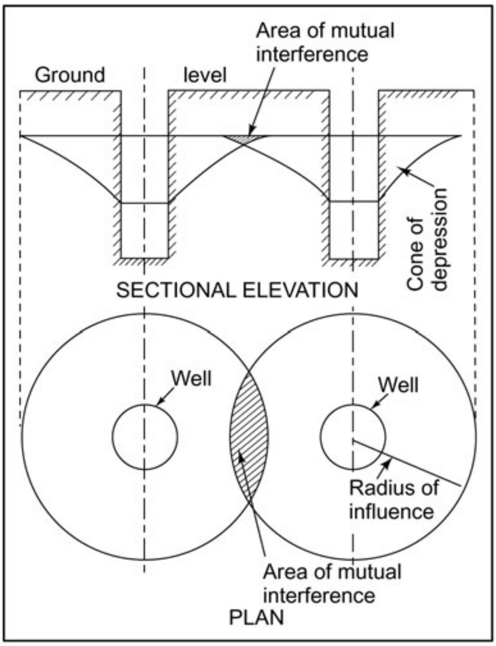

Fig. 3.9 Schematic sketch illustrating interference between closely spaced wells

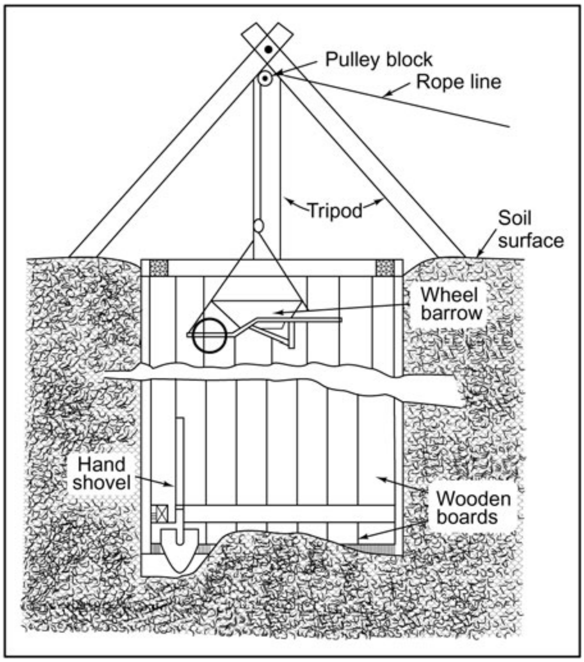

Fig. 3.10 Excavation of open well in an unconsolidated formation, using hand tools for digging and wheel barrow, operated on rope and pulley for lifting the excavated material

When digging open wells in unconsolidated formations, a carefully made continuous lining or cribbing is lowered, as the hole is deepened, to ensure safety. Temporary protection may be provided with a crib made of wooden boards (Fig. 3.10). Unless this precaution is taken, the digger's life may be endangered by a cave-in occurring at any depth greater than 1 to 1.5 metres from the ground surface. The common practice in concrete-lined wells is to allow the concrete lining to sink, as the well is deepened.

Depending upon the type of sub-soil formation met with at the site, either dug or sunk wells may be constructed in alluvial or other unconsolidated formations.

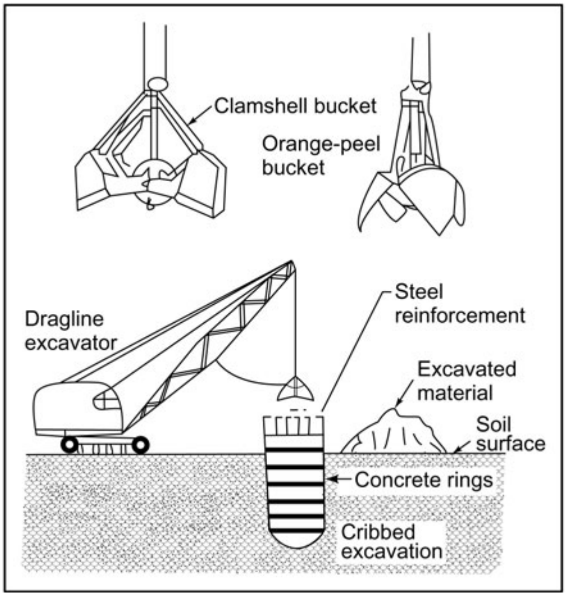

Fig. 3.11 Schematic sketch illustrating the construction of open wells using a dragline excavator equipped with orange-peel clamshell bucket. A crane of simple design, operated by a 7.5 h.p. diesel engine or 5 h.p. electric motor and provided with a manually loaded open bucket is popular in well digging in Andhra Pradesh and neighbouring regions
Source: Runa Industries, Hyderabad, A.P.

Construction of Dug Wells

When the sub-surface formation is of stable, hard soil, the construction involves the excavation of the sub-surface strata. A pit, having a diameter about 1 m larger than the required diameter of the finished well, is dug till it reaches an aquifer. The bottom of the well is located far below the water table in the summer to store a sufficient quantity of water. After digging the hole to the required depth, the masonry wall is raised with bricks or stone in cement mortar, in successive heights of 1 to 1.5 m. The brick masonry above the high-water table is sometimes plastered inside with cement mortar. The lining is raised above the ground surface to provide the well with a parapet to facilitate the lifting of water from the well and to avoid pollution through the entry of surface water. The hollow space between the natural well surface and the masonry may be filled with brick or stone ballast, or simply with earth. The earth filled in the annular space is compacted by ramming.

Even though the main flow into an open well is through the bottom, considerable increase in yield can be obtained if provision is made for water entry from the sides by providing holes duly packed with gravel and lined with a wire mesh or a perforated concrete slab on both sides of the well steining.

Construction of Sunk Wells

In open well construction, it is usually best to build the lining while diging, since this avoids temporary supports and reduces the danger of cave-ins. Sunk wells are constructed in soft formations, by sinking precast RCC rings or by constructing circular RCC curbs or wooden curbs and raising brick masonry in cement mortar over the curb. In RCC lining, a common practice is to extend the longitudinal reinforcement to allow for one or more rings to be cast subsequently. The lining is made in sections of 1 m or so, added at the top. The whole lining moves down as earth is removed from beneath. This is called *caissoning*. Often, it is necessary to add weight from the top or apply force to make the lining sink as digging proceeds. The step-by-step procedure in well-sinking is explained below:

(i) A circular pit is dug at the site of the well. The depth of the pit is such that the sides stand vertical without support.
(ii) A well curb of a slightly greater thickness than the proposed lining is laid at the bottom of the pit.
(iii) Masonry is constructed on the curb, in the form of a cylinder, till it reaches the ground surface.
(iv) A temporary circular ring platform is made on the steining, projecting half inside and half outside the steining, leaving about $1\frac{1}{2}$ m diameter space inside for removing the excavated material. The platform is loaded with gunny bags filled with sand.
(v) As the cutting edge starts penetrating under load the earth is excavated and brought to the surface by a rope-and-bucket device, or dredger. In small-scale works, the excavated material is often collected in bamboo baskets working on pulleys.
(vi) When the sinking has taken place to such an extent that the platform touches the ground, it is removed and a new section of the masonry cylinder is built on the top of the old masonry. It is taken to sufficient height above the ground surface, the platform again mounted on it, and load applied. This process is continued till the well reaches the water table.
(vii) The verticality of the well is checked during the sinking operation, using a plumb bob suspended on a tripod.
(viii) If the well starts to tilt, it is corrected by adjusting the load placed over it, or by removing the obstruction under the curb which may be causing the tilt.

The well is sunk to the required depth in successive shifts, and the platform then removed. The space between the lining and natural sides of the well wall is filled with clay and compacted. The well is finished to suit the requirements for pumping/water-lifting.

Construction of Dug-cum-Bore Wells

One of the major development schemes in the minor irrigation sector in India, since achieving independence in 1947, has been the boring and deepening of open wells to increase their yield. It has been observed that a large number of open wells in different parts of the country are amenable to improvement by boring and deepening operations. The boring is generally carried out with cable-tool percussion drilling (usually hand boring) method (Ch. 5). The percussion drilling equipment can be conveniently installed on the side of the well (hand boring sets can be installed over the well) to carry out boring in the centre of the well. Boring in an open well, with a manually operated percussion drilling equipment is shown in Fig. 3.12. A direct rotary drilling rig can be used for drilling bores in dug wells in unconsolidated formations.

The strata conditions under which boring may be expected to improve the discharge of open wells are described below:

(i) *Good water-bearing strata of small thickness underlying a layer of clay of adequate thickness* (Fig. 3.3). When formations of this nature are available, there is a good chance of increasing the well discharge by boring under such a situation. A bore ending in a cavity is to be preferred because a hard impervious layer just overlying a good water-bearing stratum is available to serve as the roof of the cavity and, secondly, the thickness of the water-bearing stratum is small.
(ii) *Good water-bearing stratum available in substantial thickness below the bottom of the well* (Fig. 3.4). In such a formation, a bore lined with strainer or slotted pipes will provide good

prospects for improving the well discharge. The well screen has to be provided opposite the water-bearing stratum.

(iii) *Two or more substantially thick layers of good water-bearing layers available in the sub-strata below the bottom of the well*. In formations of this type, a high discharge can be obtained by tapping the available aquifer by installing well screens along the water-bearing strata, with blind pipes provided along the non-water-bearing strata.

(iv) *A good water-bearing stratum available below an intervening hard rock.* There are good prospects of getting additional supplies if the hard rock is pierced through and the bore extended up to the water-bearing stratum, which may be tapped through a strainer. If, however, the water-bearing stratum is immediately below the hard rock, and comparatively thin, it may be economical to finish the bore just at the bottom of the hard rock and get the water supply through a cavity formed below the bore. Such a bore through hard rock may not be protected by any pipe as the bore in the rock is able to stand on its own.

Fig. 3.12 Boring in an open well. Note the cutter bailer ready to be inserted into the casing pipe. The cog wheel in the foreground is the drive wheel of a Persian wheel installed in the well

(v) *Artesian formation available below the bottom of an existing open well.* In such a formation, there are not only chances that the boring would increase the water supply, but also that the water level may rise considerably in the well. If the stratum of the artesian layer is thin and immediately below the intervening impervious stratum, it may be tapped without providing a well screen; otherwise a well screen may be necessary.

Any of the common methods of well drilling, namely, percussion, rotary, or down-the-hole drilling, may be adopted for boring in open wells. The drilling method and type of equipment will depend on the type of formation material encountered and the size and depth of the bore.

3.1.5 Quicksand Problem in Open Wells

Quicksand, also called running sand, is mobile, fine-grained loose sand saturated with water. It is sometimes encountered in excavations and occurs in localities where soils are underlain by lacustrine sediments or river alluvium. Open wells constructed close to foothills, downstream of dams (reservoirs) and main canals, sometimes exhibit quicksand problems, due to the saturated hydraulic pressure gradient, influencing the entry of sand particles into the well. While digging open wells, the flow of quicksand can be largely prevented by removing the material with a bucket or pump and keeping the excavation partially full of water. This neutralizes the hydraulic pressure in the quicksand and render it comparatively solid. As the excavation proceeds, the edge of the well steining should be driven 0.3 to 1.2 m below the bottom of the excavation. When a well is to rest on a sandy formation, there is a danger of sinking during operation, due to the movement of sand along with water. The well may soon get blocked with sand. Entry of sand into the pump, through the foot valve, may damage the pump. To make such wells safe against the risk of settlement and collapse, an inverted filter (Fig. 3.2) is provided at the bottom of the well. The following filter design is usually recommended for inverted filters (Jain, 1973).

Bottom 10 cm: Thin gravel, 3 mm in size
Middle 10 cm: Coarse gravel, under 1 cm in size
Top 15 cm: Stone ballast, 2.5 cm in size

Sivanappan et al. (1982), observed yield reduction in well when the total thickness of the inverted filter exceeded 30 cm. It was also observed that a 30 cm thick inverted filter was adequate to arrest sand movement into the well. Resorting to dug-cum-bore wells and placing wire mesh against weep holes were the other remedies suggested by them. Providing a large fine-mesh wire screen box to engulf the foot valve will control the entry of sand particles into the pump body.

3.2 OPEN WELLS IN HARD ROCK FORMATIONS

Open wells, in hard rock areas, often called hard rock wells, assume importance in India since about two-third of the land area of the country, comprises hard rock formations. Almost the entire Indian plateau, lying between the Vindhya Ranges, the Western Ghats and the Eastern Ghats and their adjoining areas, and the Malwa and Chotanagpur plateaus are predominantly hard rock. In addition, extensive areas of the north-west comprising large parts of Rajasthan, the Saurashtra region of Gujarat, the West Coast region extending from Kanyakumari in the south to the Tapi-valley in the north and the outer and mid-Himalayan region in the north and north-east are predominantly underlain with hard rock or semi-consolidated formations. In hard rocks are included all geological formations of low drillability in which intergranular porosity is practically absent. The different types of rock formations, their ground water characteristics and geographical locations in India are presented in Ch. 1.

The ground water formations in hard rock areas are usually shallow, ranging from 5 to 20 metres. The aquifer is directly dependent on precipitation for recharge. Hence, the water table is prone to considerable fluctuations in relation to the incidence of rainfall. The shallow ground water reservoir is constituted by the weathered mantle covering the unaltered rock, and by the fracture porosity of the unaltered rock itself. They are characterised by limited permeability. Hence, they are capable of yielding only limited quantities of ground water. Due to their poor permeability, tube wells are usually unsuitable in such formations. This is because they have to be pumped at heavy drawdowns, for considerable lengths of time, to derive even meagre supplies of water. This factor is detrimental to aquifer efficiency, due to the reduction in its saturated thickness. It is, therefore, desirable to have open wells in such formations. Open wells are capable of storing fairly large supplies of water during a given recovery period. Thus, the available supplies of water can be obtained at small drawdowns in relatively short periods, thereby allowing sufficient recuperation between successive periods of pumping. Open wells also expose a greater surface area of the aquifer for seepage into them.

In hard rock terrains where the ground water occurrence is spurious, the most important zone in which ground water invariably occurs is the weathered zone. The thickness of the weathered zones, depends upon topography, climatic conditions and rock type. Therefore, a study of the weathered zone profile, mode of weathering, structural features, and correlation of all these features with lithology are useful. In the basement rock, one can expect a good yield only if it is located in a shear, fracture or fault zone.

Dykes, which act as barriers to ground water movement, are often encountered intermittently in granitic terrain (Fig. 3.13). Dykes are actually dark coloured, medium-to-fine-grained igneous rocks occurring as intrusions in a wall-like form. They have a high specific gravity of about 3, low porosity and are very durable. They are more resistant to weathering. Unless, the rock is highly fractured and weathered, which is not common, the chances of striking water within a dyke are remote. Thus, a dyke is a good negative indicator of ground water. Dykes act as subsurface dams and effectively stop and/or change the lateral movement of ground water. On the upstream side of a dyke, one may get high-yielding wells, while on the downstream side the availability of ground water may be meagre.

3.2.1 Types of Open Wells

Open wells in hard rock areas may be dug wells or dug-cum-bore wells.

Fig. 3.13 An extensive dyke formation in the Peninsular granite region at Kushaiguda-Medchal near Hyderabad, Andhra Pradesh. There is a marked difference in water table and yield of wells between the upstream and downstream reaches of the dyke; the upstream wells having shallow water tables with substantially higher yield.

Dug Wells

Inspite of the rocky sub-stratum, well construction is undertaken in hard rock areas, as they provide the only convenient local source of irrigation and water supply. These wells are usually open, excavated pits through the rock, lined only a couple of metres (Fig. 3.14). Usually, pneumatic rock blasting equipment, using jack-hammers and explosives, is employed for the excavation of the well through hard rocks. Ordinary horizontal centrifugal pumps are commonly used for pumping water from the open wells. The inside view of an open well in a fissured formation fitted with a motor-driven centrifugal pump is shown in Fig. 3.15.

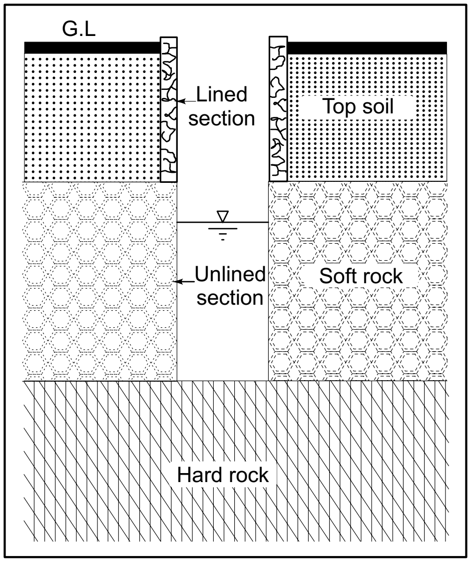

Fig. 3.14 Schematic sketch of a dug well in a hard rock formation

Dug-cum-Bore Well

Boring of dug wells in hard rock areas, to augment their discharge, has been gaining popularity. Boring helps to tap embedded water-bearing materials, if existing underneath, as in the case of the Deccan trap areas. Boring also helps to tap additional fissures and cracks in crystalline hard rock areas, even if embedded layers of water-bearing materials are not available. A dug-cum-bore well is shown in Fig. 3.16. Normally, boring in dug wells in hard rock areas has to be carried out either by percussion-drilling rigs, which can be erected over the open well, or calyx drills, which can be lowered down to the bottom of the well (Ch. 5). Boring by percussion or calyx rigs is a slow process. Lately, in some areas, boring of slender holes of 4 to 5 cm diameter, in different directions, by using rock drills with extension equipment, has been observed to be effective in increasing the discharge of hard rock wells. Drilling in such wells is also carried out by small down-the-hole rigs which can be carried down to the bottom of the well (Ch. 5).

It may be seen that several types of operations (deepening by blasting, large diameter central borings, slim boring in different directions, etc.) are available to augment the discharge of dug wells in hard rock areas. The comparative efficiency and merit of each of these operations, depend upon local hydrogeological situations.

3.2.2 Design Procedure for Open Wells

General guidelines outlined for determining the capacity of wells, based on water requirements and their locations, apply to hard rock wells also. Analytical procedures for designing and locating wells in hard rock areas are difficult to develop due to non uniformity in the fissures or pore spaces in hard rocks. However, useful guidelines have been developed for the design of hard rock wells. Based on the studies conducted at the Hyderabad centre (Osmania University) of the ICAR co-ordinated project on wells and pumps, the following criteria have been developed for the design and location of open wells in the hard rock areas of the Deccan plateau:

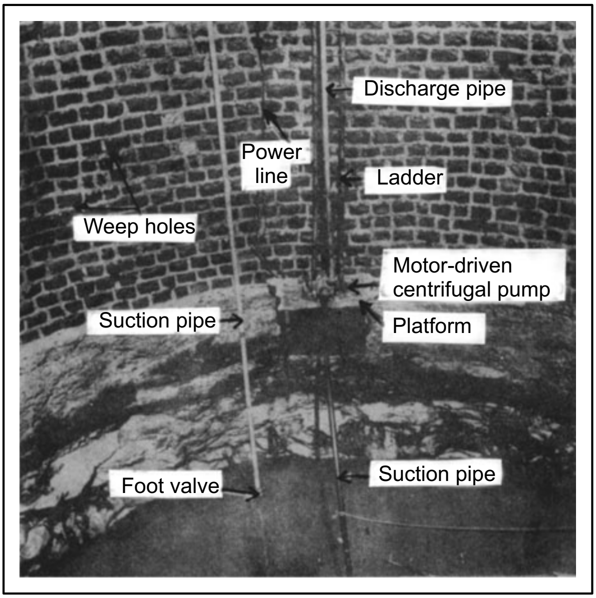

Fig. 3.15 Inside view of a partially lined well in a fissured formation. Lining is confined to the upper subsoil formation. Of the two pumping sets installed in the well, the suction line of the one located near the top of the well is seen while the lower pumping set is seen beside it

(i) In the case of hard rock terrains, open wells, rather than bore wells, are recommended. Open wells can tap the weathered zone better than bore wells and are cheaper for shallow depths.

(ii) In hard rock areas, a large rectangular open well is preferable to the traditional circular well. Large cross-sectional areas have greater chances of cutting across fracture zones and thereby increasing recharge into the well. This provides provision for the storage of large amounts of water.

(iii) The longer side of the rectangular well should be normal to the direction of the fracture system to ensure better yield.

(iv) Dug wells in granitic areas should touch the basement rock. This is because the top of the basement rock is a more fruitful zone than the remaining part of the weathered zone.

(v) It is advisable to tap granites (for ground water) rather than Deccan traps, when both are present in the same area.

(vi) In the case of sedimentary formations, open wells (or tube wells) should penetrate the entire thickness of the aquifer.

(vii) Since dykes act as barriers to ground water flow, in the vicinity of a dyke, wells should be located only on the upstream side of the dyke strata. Except when the dyke is very much fractured and weathered, which is rare, wells should not be located on the dyke or downstream from it.

(viii) Wells located in pink granitic terrain have better chances of greater yield, than those in grey granite areas.

(ix) It is not advisable to deepen a dug well beyond the weathered zone. Instead, bores at its bottom could improve the well yield. These bores should be on the side where fissures or fractures are present. They can be radial, vertical or inclined, depending upon the characteristics of the strata.

3.3 DEEPENING OF OPEN WELLS

Deepening of wells consists of blasting the bottom of the wells to the rocky sub-stratum with dynamite, in stages upto the desired depth. This is resorted to in cases where boring is not likely to help. The objective of deepening are two-fold: (i) to expose additional water-bearing joints, cracks, crevices, etc. and (ii) to increase the storage capacity of the well. Wells in drought prone areas often require deepening due to the lowering of the water table.

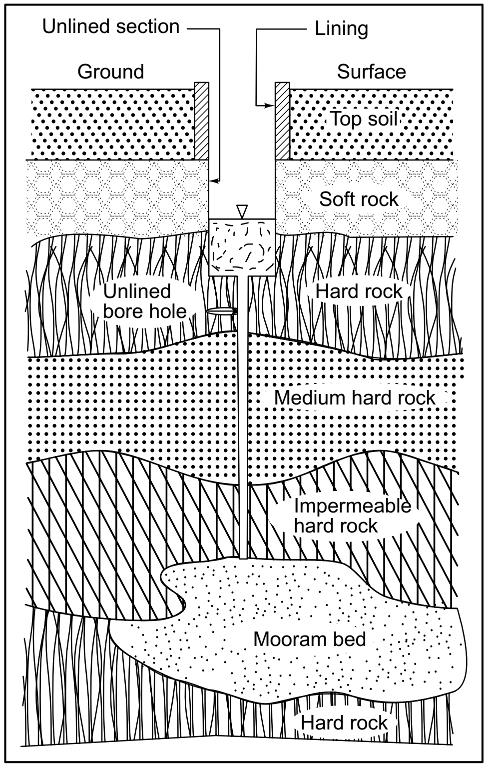

Fig. 3.16 Sectional view of a dug-cum-bore well in hard rock tapping an inter-trappean mooram bed

Rocks normally contain voids, interstices, cracks, joints and bedding planes. They serve as receptacles for holding water. In most rocks, these are inter-connected so that a constant circulation of water is maintained under gravitation and hydraulic forces. In some rocks, however, these are generally isolated and there is little opportunity for water to flow. In such rocks, where inter-connections are not sufficiently developed, percolation can be increased by deepening the existing wells. Deepening also enables exposure of a larger volume of the weathered zone, thus increasing the well yield.

Dug wells in alluvial formations can be deepened manually. There are tracts where soft rock appears after the first few metres of the top soil have been removed. Manual deepening becomes increasingly difficult under such situations. Similarly, manual deepening is not feasible in hard rock regions. Careful blasting by modern procedures make deepening of open wells easy and economical.

3.3.1 Types of Explosives

Gunpowder is the oldest known explosive. It was used to propel fire arms in the thirteenth century. It was first used for blasting at about the middle of the seventeenth century. The gunpowder is tamped in holes drilled in rocks, using chisels and hammers. It is ignited with a safety fuse or fuse lead. The main difficulty in the use of gunpowder in blasting, is the hazard involved in setting it off. In the deepening of wells, another limitation is the difficulty in working after the water table is reached.

A major development in the safe use of explosives in blasting was the invention of the safety fuse in 1831 by William Bickford. The next important step in the development of blasting explosives was the development of high explosives in the middle of the nineteenth century, when nitro-cotton and nitro-glycerine were discovered and introduced in blasting operations. The invention of the detonator by Alfred Nobel of Sweden, in the later part of the nineteenth century, provided a means for safe and reliable initiation of modern explosives.

3.3.2 Classification of Explosives

There are three classes of authorised explosives in India.* They are gunpowder, nitrate mixture and nitro-compound. *Nitrate mixture* is any preparation, other than gunpowder, which is formed by the mechanical mixture of a nitrate with any form of carbon or carbonaceous substance, which is not having explosive properties. *Nitro-compound* is any chemical compound which has explosive properties or is capable of combining with metals to form an explosive compound. It is produced by the chemical action of nitric acid or of a nitrate mixed with sulphuric acid upon any carbonaceous substance. Every blasting explosive in the later two classes, in which ammonium nitrate, sodium nitrate or sodium chloride, or nitroglycol are used as ingredients are contained in cartridge wrappers, or cases which are made water-proof with melted paraffin wax or other suitable wrapping material.

Blasting explosives are almost exclusively nitro-compounds. Nitro-glycerine is the predominent material in blasting explosives. Nitro-compound type blasting explosives, are usually marked 'S' and are sheathed on the outside of the cartridge with an approved sheathing material. The outer wrapper of a sheathed cartridge is of adequate strength to prevent the escape of any of the sheathing material, when the cartridge is submitted to any jolt. Explosive cartridges are subjected to heat test and jolting test, as specified by the law of the land.

Based on the nature of explosion that is produced, modern explosives are grouped into three classes, viz. initiating explosives, high explosives and low explosives.

Initiating Explosives

These are extremely sensitive and easy to explode. They are used to initiate the detonation of high explosives. When ignited, they produce an intense local shock, which is capable of starting the reaction in the high explosives which are less sensitive. They do not produce large volumes of gases and are not suitable for direct use in blasting operations. They are loaded in small quantities in copper or aluminium tubes, to form detonators and in this form are used as prime charges of high explosives.

High Explosives

High explosives detonate at velocities varying from about 1,500-7,500 m/s, depending on the explosive composition. Large volumes of gases are produced at very high pressures. The reaction is started by a shock wave initiated by a detonator. The shock wave developed in the explosives causes fractures in the rock, and this action is followed by the formation of high-pressure gases which complete the destruction. The performance of a high explosive depends on the volume and temperature of gases produced and the velocity of detonation. High explosives are used for all blasting operations, except where a very gentle heaving action is required.

* Department of Explosives, Govt. of India, Notification No. E-11 (7) of July 11, 1969.

Low Explosives

In low explosives, the reaction consists of a very rapid turning of the explosive composition without the production of an intense shock wave. Usually they are set off by a flame or a spark from a safety fuse or fuse head. The only type of low explosive in common use is gunpowder. Low explosives are used where a gentle heaving action is required. For effective use, it must be well tamped.

Blasting Gelatine

Blasting gelatine is the most powerful of all commercial explosives. It was discovered by Alfred Nobel in 1857 and, to this day, it maintains its superiority in the field. It is a high-density gelatinous explosive with good storage qualities, and is unaffected by water. However, to ensure a high velocity of detonation, special priming is necessary. The main constituents of the gelatines are nitro-glycerine, nitro-cotton and sodium nitrate.

High explosives (gelatines), commonly used in rock blasting operations in wells, are of 2.5 cm diameter and 20 to 25 cm length. They are available in India under trade names of Special Gelatine (IEL*), Superdyne (IDL**), Formedyne (IDL), etc. They are usually available in strengths of 90%, 80%, 75%, 60%, 50%, 40% and 30%. Gelatines of 80% strength are commonly used in well-deepening work. However, when the strata are particularly hard, gelatines of 90% strength are to be used.

3.3.3 Properties of Explosives

The main properties of explosives include:

(i) Strength of explosives
(ii) Velocity of detonation
(iii) Density
(iv) Water resistance
(v) Fume characteristics
(vi) Resistance to low temperatures

Strength of Explosives

The strength or power of an explosive is a measure of the amount of energy released by it on detonation. Hence, it is its ability to do useful work. Of the several methods of expressing the strength, the most common is that calculated on the basis of the deflection of a freely suspended ballistic mortar, in which small explosive charges are fired. The grade-strength of an explosive is the percentage of nitro-glycerine in the pure nitro-glycerinc dynamite, that produces the same deflection on the ballistic mortar as an equal weight of a reference explosive. The commonly used comparison is to designate the strength of an explosive as a percentage of that of the blasting gelatine, which is the most powerful amongst the commercial explosives.

Velocity of Detonation

The rate at which the detonation wave travels through a column of explosives is known as the velocity of detonation. With most commercial explosives in common use, the velocity obtained is generally of

* IEL: Indian Explosives Ltd.
** IDL: Indian Detonators Ltd.

the order of 2,500 m/s. However, the velocity of detonation obtained by initiation with a strong primer, is much higher and may be of the order of 5000-7000 m/s. High velocity explosives are preferable for special purposes such as metal-breaking and underwater work. Low velocity explosives are preferred where excessive shattering is to be avoided.

Density

The density of an explosive is important in determining its suitability for blasting operation. The density depends on the ingredients. With a high density explosive, the energy of the shot is concentrated, which is a desirable feature in tunnelling and mining operations in hard ground.

Water Resistance

Explosives differ widely in their resistance to water and moisture penetration. When blasting is to be done under wet conditions, an explosive of good water resistance is chosen. Explosives which have a low water resistance are cartridged in special wrappers and dipped in a protective wax for storage.

Fume Characteristics

All explosives produce a certain amount of fumes on explosion. Modern explosives have their ingredients carefully adjusted so that toxic fumes are controlled and kept to a minimum. Adequate precautions for ventilation should be taken, especially in confined spaces.

Resistance to Low Temperatures

Explosives which contain nitro-glycerine tend to freeze at temperatures below 8°C. Suitable ingredients are often added to enable the explosives to be used at temperatures as low as –20°C.

3.3.4 Blasting Accessories

Detonators, exploders and hand-held pneumatic rock drills are the main accessories required in rock blasting. Careful selection of accessories in a blasting operation is as important as the selection of the right type of explosive.

Electric Detonators

Detonators are required to initiate the blast by explosives. Submarine electric detonators are suitable to withstand high pressures. Detonators consist of an aluminium tube, filled with a base, charge of PETN (pentaerithritol-tetra-nitrate) and a lead azide based primary charge, both consolidated under pressure. One end of the tube is closed, and to the other end are attached the lead wires. These lead wires are insulated with PVC tubing and enter the detonator body through a water-proof plug. All detonator lead wires are shunted (end-twisted) to protect against stray currents.

Electric detonators may be of two types:

(i) *Instantaneous detonators*
(ii) *Delayed detonators.*

Instantaneous detonators are used for the simultaneous firing of all the explosives on a job field (Fig. 3.17).

Delayed detonators can be set to stagger the firing to suit a pre-determined sequence on a job. Delayed detonators have an additional delay element between the fuse head and the priming charge. The delay element is designed to obtain the required delay interval, which is usually a fraction of a second. The delay pattern of short-delay detonators may be a few milli-seconds, while in long delay types it may be as much as 500 milli-seconds (half second) or more. In blasting operations in wells, the types of delay detonators are chosen so as to provide progressively increasing delays from the centre to the periphery of the rows of shot holes.

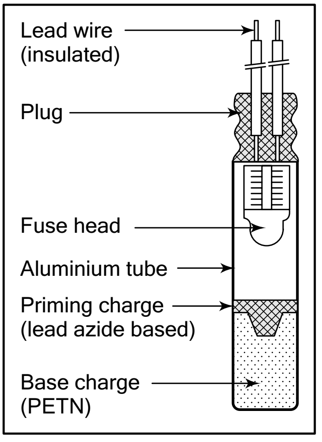

Fig. 3.17 Sectional view of instantaneous type detonator *Courtesy:* Rajasthan Explo. and Chem. Ltd., Dholpur

Exploders

Either electric or safety fuse shot firing can be employed in well sinking. The safety fuse, which was the only means of igniting explosives in earlier days, consists of a thin core of black powder (gunpowder), wrapped in layers of jute textiles and provided with water-proof coating. However, electric exploders, have almost replaced safety fuses in well-deepening operations. When explosives are to be initiated electrically, either singly or in series, an exploder of adequate capacity must be used. A variety of exploders have been developed for particular needs in the field. The following are some common types of exploders used in rock blasting:

(i) *Magneto exploder*. It is operated by twist-action detachable handle and is suitable for firing upto six shots simultaneously.

(ii) *Dynamo-type exploder*. Suitable for series firing and operated by a twist-action detachable key—a device whereby no current is passed through the firing circuit unless the armature has attained a minimum speed. This ensures that a round of shots does not partially misfire due to faulty operation of the exploder. It is used for series firing in quarries.

(iii) *Dynamo-type heavy-duty exploder*. It is operated by turning a handle. The A.C. voltage generated is stepped up by a transformer, rectified and used to charge a condensor to a potential of not less than 1,200 V. When the firing button is pressed, the condensor is discharged through the circuit, firing the shots. It is suitable for use in tunnelling operations and quarries, for firing up to 100 shots in series.

All exploders have removable firing handles or firing keys. The shot firer (operator) responsible for connecting the shot or round of shots is required to keep this key or handle in his personal possession while the shots are being charged or connected. It should never be left in the exploder.

Loading Explosive Cartridge with Detonator

To load the primer cartridge with an electric detonator, a hole is made at the end of the cartridge with an aluminium, brass or wood pricker. The detonator is inserted until it is completely buried in the explosive. The lead wires are hitched around the cartridge, to prevent the detonator from being withdrawn accidentally during loading in the drill hole.

Shot Hole Drilling Equipment

The equipment used for drilling shot holes in rocks comprises hand-held rock drill (Fig. 3.18), often called jack hammer, consisting of the drill body with a piston operated by compressed air, drill chuck and handle. The rock drill works on percussion and rotary actions with the energy imparted by compressed air. The automatic rotational system consists of a rifle bar, rifle nut, piston and chuck nut, together with a ratchet ring, pawls and other minor parts. On an average rock drill, the piston reciprocates about 1800 to 2000 times per minute. The drill should work at the rated pressure. Air consumption of hand-held drills, operating at 6 kg/cm^2 pressure, varies from 2 to 3.5 m^3/min., depending on the type of drill. They are of air-flushed or water-flushed types. Water-flushed drills (Fig. 3.19) are preferred in rock blastic operations in wells.

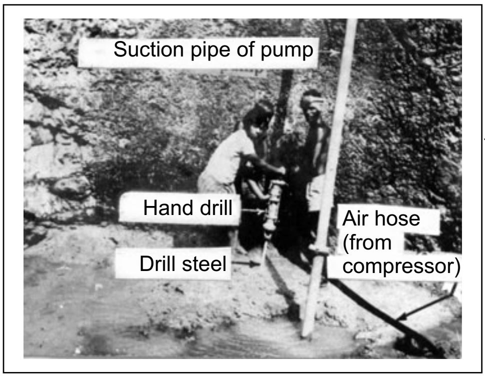

Fig. 3.18 Drilling of shot hole at the bottom of a hard rock well with a hand drill equipped with integral steel rod. Note the suction pipe of the pump used to lower the water table during drilling

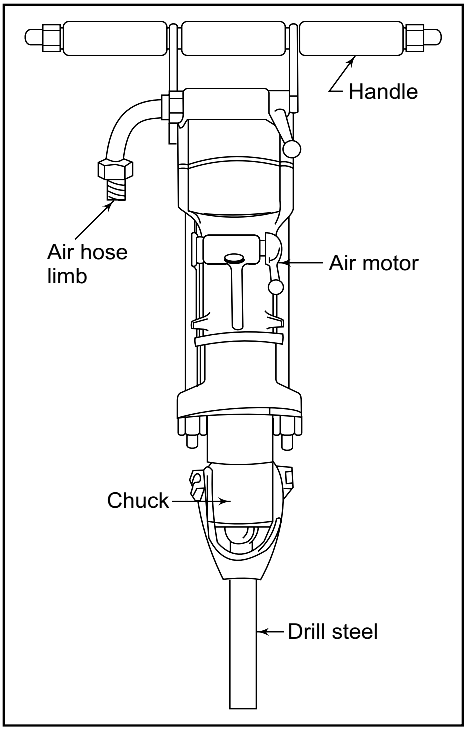

Fig. 3.19 Hand-held water-flushed rock drill (Jack hammer) suitable for shot hole drilling and horizontal drilling in open wells
Courtesy: Atlas Copco (India) Ltd., Mumbai

Rock Drill Maintenance

The rock drill is subject to considerable stress and strain which require care in its operation. The two essential requirements of correct operation are adequate lubrication and correct air pressure. Lubrication is provided by an *air line lubricator* which forms an essential accessory to rock drills. Air pressure is maintained by proper controls and good maintenance of the air compressor and accessories.

Field maintenance of rock drills consists principally of lubrication, keeping the drill clean and all bolts and nuts tight. Worn piston faces, chucks, shank and bits of drill steel are frequent sources of troubles in rock drills. While repairing a drill in the shop, the striking face of the piston is kept as square and flat as possible. A worn chuck allows the drill steel to become misaligned so that the piston strikes the edge of the drill rod, thus tending to chip and spall both the face of the drill rod and the piston (Fig. 3.20). Off-centre hammering on the piston end introduces side strains resulting in breakage. Wear and mal-functioning of component parts result in excessive air leakage and consequent loss of blowing power.

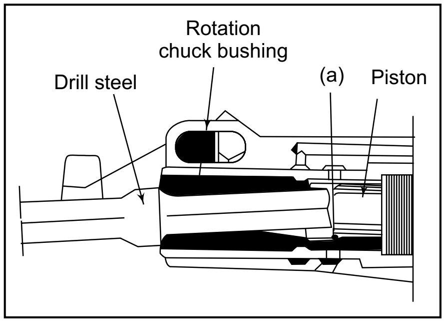

Fig. 3.20 Result of worn bushing of rotation chuck in a hand held rock drill. The piston strikes the drill steel obliquely, damaging both of them
Courtesy: Atlas Copco (India) Ltd., Mumbai

Integral Drill Steels

An integral drill steel used with hand drills for shot hole drilling consists of a rod with a forged shank and collar at one end and a forged bit with cemented tungsten carbide inserts at the other (Fig. 3.21). At the bit end, the flushing water is discharged through a drilled hole at the side of the bit. Each steel is of specified length and cannot be extended. Drilling is done in stages. When the first integral drill steel has been drilled into the rock, it is withdrawn and replaced by a longer one and so on till the shot hole is drilled to the required depth. At each stage, the diameter of the drill steel is reduced to prevent the drill from becoming jammed in the hole. Integral drill steels are arranged in series, with their diameter decreasing with increasing steel length. The size of the final rod in the series is equal to the diameter of the explosive cartridge used. The length interval between the steels in a series is governed by the feed length of the drill. The following are the sizes of the drill steel commonly used in rock blasting in wells:

Length of drill steel	Size of shot hole
800 mm	32 mm
1600 mm	31 mm
2400 mm	30 mm

Chisel-type steels (Fig. 3.21) are most commonly used in drilling shot holes in rocks. They are easy to sharpen and are most economical under normal drilling conditions. Multi-insert steels are preferred for drilling in soft and fissured rocks. Integral steels with button bits are used in easily-penetrated soft rock.

3.3.5 Blasting Procedures

The various operations in rock-blasting for the deepening of open wells include the layout and specifications of shot holes, charging of explosives and firing procedures.

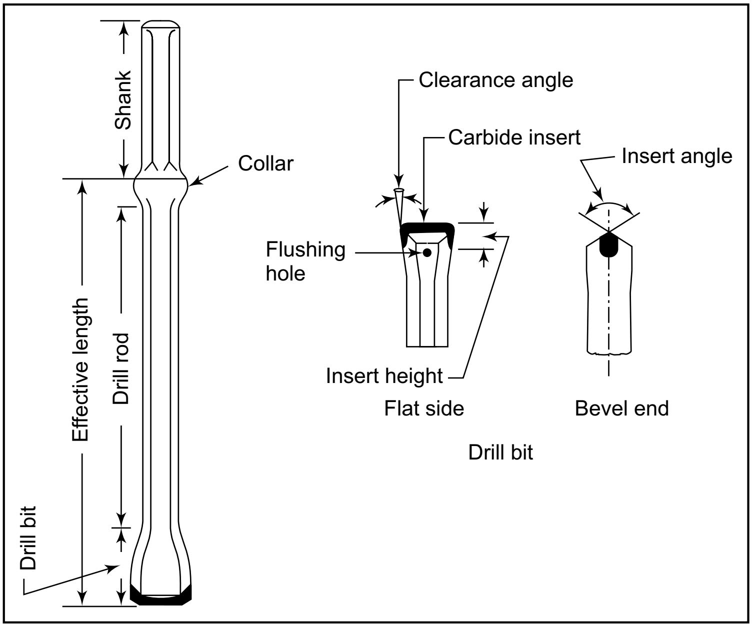

Fig. 3.21 View of a chiesel-type integral drill steel.
Adapted from: Anderson, et al., (1978)

Shot Hole Specifications and Layout

For the 25-mm diameter explosive cartridges commonly used in rock blasting, the diameters of shot holes range from 30 to 33 mm. The depth of shot hole commonly used in rock blasting in open wells is 1.2 m (vertical), to ensure an efficient job. Shot holes are usually grouped into three classes: cut holes, easer holes and trimmer holes (Fig. 3.22). *Cut holes* are drilled oblique to minimize the resistance to blast and enable the explosive force of the blast to be more effective in breaking the rock. Oblique cut holes prevent the explosives from shooting out straight, as they sometimes do if they are vertical and the charges are not properly tamped. *Cut holes* are usually inclined at about 66° to the horizontal. They are spaced about 60 cm apart. *Easer holes* are usually inclined at 70°-80° to the horizontal and spaced slightly farther from each other than cut holes. *Trimmer holes* are close to the periphery of the well. They are spaced farther than *easer holes*. In general, the spacing between holes varies from 60 to 75 cm. The effective surface area of rock covered by one shot hole varies from 0.3 to 0.5 sq. m. (3000 to 5000 sq. cm). Figure 3.22 shows a typical layout of shot holes in a circular well in a medium-hard rock formation. The spacing between shot holes varies with the type of rock formation, the harder the rock the closer the spacing.

Charging of Explosives in Shot Holes

The progress of fire in a shot hole is from the bottom to the top. Hence, an explosive cartridge loaded with the electric detonator, called the primer cartridge, is placed at the bottom of the shot hole. The lead wires are laid to one side of the shot hole, with their ends projecting out for connection to the firing cable. As the dynamite is plastic, it can be compacted in the hole to obtain a high concentration.

Charging can be done by dropping the cartridges into the hole and tamping them into place with a pole or a heavy plumb line. With shot hole diameter ranging from 64–102 mm, it is usual to use cartridges of size about 10 mm smaller than the hole diameter and these are dropped into the hole without tamping. The extent of charging of explosives in shot holes varies with the type of hole. Cut holes are about 90 per cent filled, easer holes 45-60 per cent, and trimmer holes about 45 per cent. The remaining space in the shot hole is filled with clay sticks, the process being called stemming. The average yield of the explosive gelatine used in rock blasting in wells is about 2 m^3 per kg of the explosive.

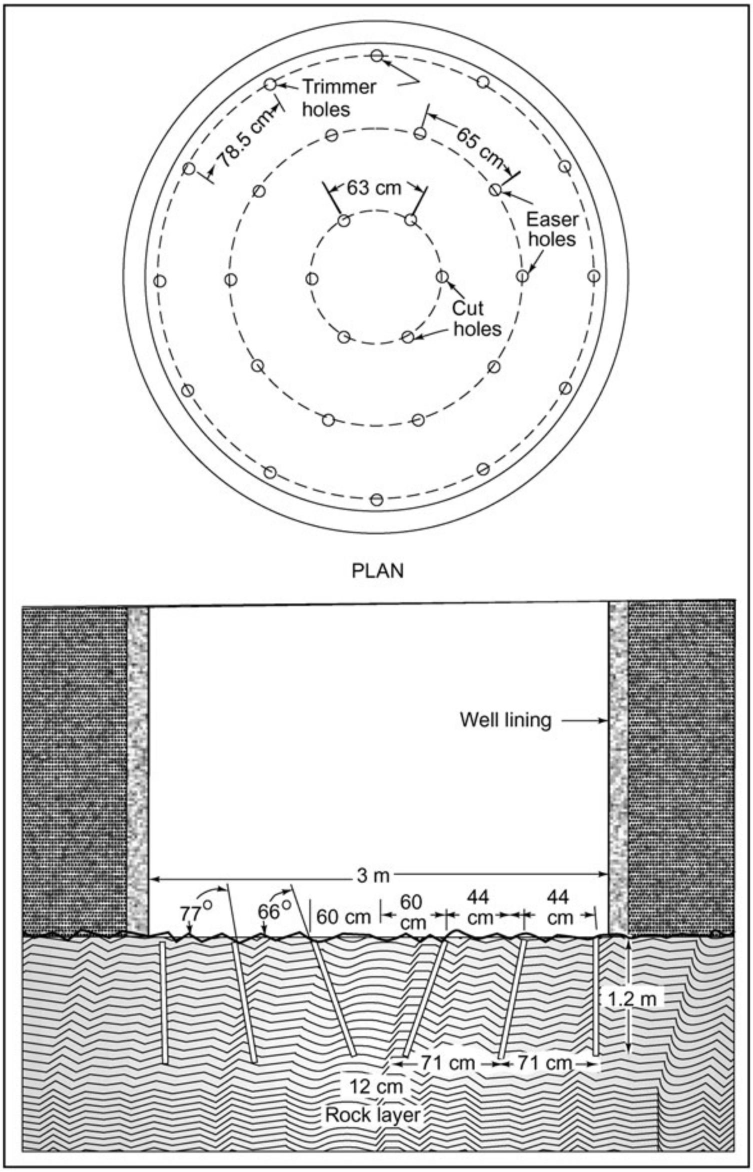

Fig. 3.22 Views of a 3 m diameter circular well showing a typical layout of shot holes for blasting

The delay pattern of electric detonators is so selected as to allow the firing in sequence, from the centre to the periphery. Thus, detonators with zero delay (instantaneous type), are used in easer holes, and those with maximum delay setting in trimmer holes. It also results in a better spread of the broken rock, which facilitates easy removal through buckets.

Firing Pattern

Shot-firing operations in rock blasting involve the simultaneous firing of a number of charges, adopting predetermined delay patterns. The method normally employed, is to fire a number of electric detonators, connected with the exploder through the shot-firing cable, in simple series circuit. Occasionally, it may be desirable to use a parallel circuit. However, when firing with an exploder, a parallel circuit should not be used, when the number of detonators exceeds three.

When firing a number of detonators in series, it is recommended, that a minimum current of 1.5 A is passed through the circuit. The voltage necessary to pass this current can be calculated from *Ohm's law* ($V = IR$, in which V is the required voltage, I = current in amperes and R = total resistance of the circuit in ohms (Ω)). The total resistance is the sum of the individual resistances of the shot firing cable, lead wires and detonators. For rough estimates, the resistance of a shot-firing cable is assumed as 5 Ω per 100 m, that of the connecting wire as 8 Ω per 100 m and of the detonator as 2 Ω. However, it is always better, to measure the resistance of the circuit with an ohm-meter, often referred to as *blastometer* (in blasting practice). To ensure full initiation of the explosives, it is safe to provide about 50 to 100 per cent additional voltage than the estimated value. In practice, however, an exploder is rated to fire a given number of shots, and its margin of power is such that it will take care of any reasonable and normal additional resistance, such as that of the shot-firing cable.

When firing a number of shots electrically in series, the charging procedure is similar to that used in single-shot firing, but the lengths of the lead wires extending outside the hole are wound into neat coils until all the shot holes are charged. In damp conditions, joint insulators are used to prevent current leakage which might cause misfires. It is ensured that all the detonator wires are correctly connected to obtain the desired firing pattern. The shot-firing cable is tested for continuity and insulation and then connected to the two ends of the detonator circuit.

When ready to fire, the shot-firer should make sure that men working in the vicinity have moved to a safe position and that all approaches to the blasting site are guarded. The complete circuit is then tested from the firing point and the shots fired. After it is ensured that all the shots are fired, the debris is removed in buckets working on pulleys and lines or with mechanical excavators equipped with suitable buckets.

When well sinking is done near buildings and in built-up areas, care should be taken to minimize vibrations. Vibrations can be minimized by reducing the amount of charge fired at a time and by using delay detonators. Flying-debris can be controlled by covering the top of the well with strong wire nets weighted with sand bags.

General Precautions in Blasting

It is essential to ensure safety in blasting. Some of the major precautions are given below:

(i) Only persons with proper training and licence are appointed as shot firers.

(ii) Smoking or the use of naked lights should be prohibited when handling or working in the vicinity of explosives. (There is a hazard with all explosives, but black powder and detonators are specially susceptible to premature initiation by spark or flame.)

(iii) When firing a round of shots using a safety fuse, make sure that the method of firing allows time for the full number of shots to be ignited, and that the fuse lengths are adequate for the shot firer to move to a safe distance. Make sure that the fuse is not damp and is not damaged during stemming.

(iv) When straightening the lead wires, do not hold the detonator by the tube. Grip the wires about 8 cm from the detonator, with one hand, and smooth the lead wire with the other. This will avoid any pull on the electric fuse.

(v) When inserting the primer cartridge in the bore hole, see that the wires are straight. Kinks are untwisted gently. To jerk them out may break the wires and cause a misfire.

(vi) While charging and in storage, care is taken to avoid damaging the covering of the wires of electric detonators. Stripping the wires is a possible cause of misfire.

(vii) See that the lead wires are long enough to allow good connections with the cable.

(viii) Before deciding that a shot has misfired, carefully examine the cable and all the connections and test the circuit with a circuit tester.

(ix) To ensure good insulation in wet holes, junctions are securely covered with insulating tape or joint insulator.

(x) Avoid electric shot firing near overhead power cables.

(xi) Avoid handling explosives during the approach or progress of an electrical storm.

(xii) The handle of the exploder is always kept in the personal custody of the shot firer.

(xiii) Before returning to a shot, first disconnect the cable from the exploder and remove the firing handle.

(xiv) Never drag the firing cable along the ground. It should be carefully coiled and carried. Similarly, care is taken to avoid kinks in the firing cable, as these lead to internal breaks which are difficult to trace.

(xv) Avoid drilling a bore hole near another hole loaded with explosives.

3.3.6 Legal Aspects on Use of Explosives

Every country has its own specific legal requirements on the use of explosives. The Indian Explosives Act, 1884, regulates the manufacture, storage, possession, use, sale, transport and importation of explosives in India. The Indian Explosives Rules, 1914 and 1940 and other rules made by the Central and State (formerly Provincial) Governments give specific guidelines on the subject. The Indian Explosives Act has laid down the general law as to the manufacture and storage of explosives, prescribing the places at which an explosive may be manufactured or kept. It also deals with the licensing and regulating of factories and magazines. Specific rules exist on matters relating to inspection, search and penalties. The Chief Inspector of Explosives in India, under the Department of Explosives of the Ministry of Works, Housing and Supply, Government of India, is the competent authority to enforce the provisions of the Act and the laws framed under it.

Licences for the handling of explosives are issued by the Chief Inspector of Explosives in India or other offices duly authorised for the purpose, depending on the nature of the use and the size of work. A person desiring to obtain a licence shall apply in the prescribed proforma, to the authority empowered to grant such a licence. For small scale projects like deepening of wells, when the quantity of explosives is limited to 50 kg, the licensing officer is usually the Revenue officer of the District (Collector/Deputy Commissioner).

3.4 INCREASING THE YIELD OF OPEN WELLS

Low yield is often a problem in open wells, especially in hard rock areas. The main causes of low yield in wells are a poor aquifer, mutual interference of neighbouring wells, inadequate depth of well with reference to potential water-bearing formations, improper location of wells, and presence of underground barriers upstream of the well. The following are the common methods adopted to increase the yield of open wells:

(i) Deepening of wells to tap potential water-bearing formations adequately.
(ii) Providing one or more vertical bores at the bottom of existing wells to penetrate potential water bearing layers lying below it.
(iii) Providing horizontal bores along the sides of wells below the water table, or installing filters radially in potential aquifers.
(iv) Rescheduling of pumping time into convenient block periods.
(v) Increasing ground water recharge in the vicinity of open wells.

Procedures for deepening wells and installing vertical bores at the bottom of open wells (dug-cum-bore wells) have been discussed in preceding sections.

3.4.1 Horizontal Boring in Open Wells

Studies have shown that in many ground water regions, especially in semi-consolidated and hard rock formations, the yield of existing open wells can be increased substantially by drilling horizontal bores below the water table. These borings, sometimes called *revitalization holes*, open the paths of flow in water-bearing formations, which may otherwise be restricted. They also function as miniature horizontal wells or infiltration galleries leading to the main well, thus increasing the well discharge. Since a good part of the ground water in hard rock areas is stored in cracks and fissures of rocks, the lateral flow of water may often be slow. At a certain distance from a well which has gone dry, the water table may be considerably higher than that in the well itself. Because of this hydrostatic head, water often comes out of revitalization holes by its own pressure. Sometimes underground barriers (dykes) obstruct the flow of water into hard rock wells, from upstream. In such a situation, horizontal boring to pierce the barrier layer may greatly increase the yield of the wells. However, it is feasible only if the barrier is of narrow width and lies close to the well.

Installation of Radial Filters in Wells in Alluvial Formations

Studies on the methods of increasing the yield of open wells in alluvial formations have indicated significant increases in yield on installing filters radially (Khepar and Sondhi, 1973). Unlined radial bores, however, are not feasible in these wells since they will be blocked by the collapse of the unconsolidated aquifer material. Filters can be installed through suitable radial boring equipment. Jackscrew based manually operated, radial-boring equipment (Fig. 3.23) is suitable for installing filters radially in open wells.

The design details of radial boring equipment for alluvial formations, are given in Fig. 3.23. The equipment consists essentially of a jack screw working on a pipe vice. The jackscrew is made of 10 cm dia. mild-steel pipe, 6 mm thick and about 1 m long, with external square thread on about 80 cm of pipe. The jackblock consists of a 25 cm long pipe with internal threads matching those of the jack screw block. The jack block is held in a pipe vice fixed on a suitable work table which is provided with adjustable legs. The adjustable legs facilitate the alignment of the equipment at the point where the filter is to be installed. Three rods are welded radially to the jack block, at a spacing of 120°, to serve as handles to operate the screw. Each handle is about 1.5 cm in diameter and 45 cm long. At the end of the jack block is fixed a reducer pipe of about 10 cm × 8 cm. The smaller diameter of the reducer pipe is kept slightly larger than the outside diameter of the filter which is to be installed in the well. Three screws, spaced 120° apart, are provided in the reducer to lock the filter while driving it into the water-bearing stratum.

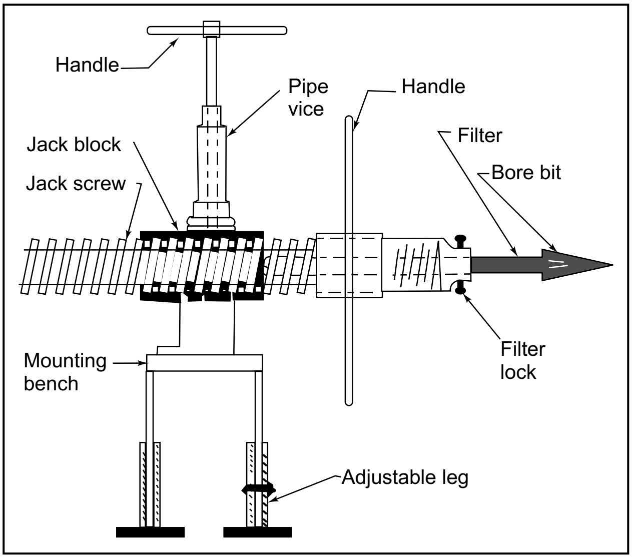

Fig. 3.23(a) Details of radial boring equipment for installing filter in open wells

Fig. 3.23(b) Radial boring equipment in operation in an open well

Any common type of filter pipe used in shallow tube wells, viz., a pipe-based well screen with coir or wire-netting envelop, can be used. The size of the filter pipe ranges from 2.5 to 6 cm in diameter. They are available in lengths ranging from 1 to 3 m. The drive end of the filter is provided with a conical metal point. The base of the conical bit is kept slightly larger than the filter diameter.

To install the filters, the water level in the well is lowered to the desired depth by continuous pumping. Points are then marked on the well wall, where the filters are to be installed. The equipment is lowered into the well and properly installed with reference to the point where the filter is to be located. The steining of the well is broken at the point marked. The filter is then loaded in the jack block and locked. It is driven into the formation in suitable lengths. When the full length of a filter has been penetrated, another piece is screwed in and the procedure repeated. The length of filter is usually limited to 3-5 m when manually operated jack blocks are used.

Radial Boring in Open Wells in Semi-Consolidated Formations Using Manually Operated Augers

The yield of open wells in semi-consolidated formations can often be improved through radial bores which usually extend 15-25 m into the water bearing formations. There is considerable local skill in Rajasthan and adjoining regions to make horizontal bores in semi-consolidated formations, with indigeneous hand-boring tools consisting of sharp, pointed or twisted bits of about 2-3 cm size and extension pieces. The extension pieces consists of 2-2.5 cm square rods in 1-1.5 m length, with two bolt holes at each end for joining adjacent piece. Boring is done with a twisting and reciprocating motion of the auger set. While making horizontal bores, the water level in the well is kept below the level of work. This is done by pumping or employing one or more animal-operated water lifts, like leather buckets. A suitable thumb rule for locating the points for radial boring in semi-consolidated formations is to follow the track of water oozing out of the crevices.

Radial Boring in Hard Rock Wells with Mechanically Powered Equipment

It is often not possible to make horizontal bores in hard rock wells with manually operated equipment. Mechanically operated equipment, consisting of an air compressor and rock-drilling kit with pneumatic feed, are used to make horizontal bores in hard rock wells (Fig. 3.24). A jack hammer (rock drill) is mounted on an auto-feed (Figs. 3.25 and 3.26). The jack hammer is operated by compressed air from an air compressor of about 7.5 kg/cm^2 pressure and 5 m^3/min capacity. The air compressor is kept on the ground surface close to the well, and compressed air is fed through hoses of adequate

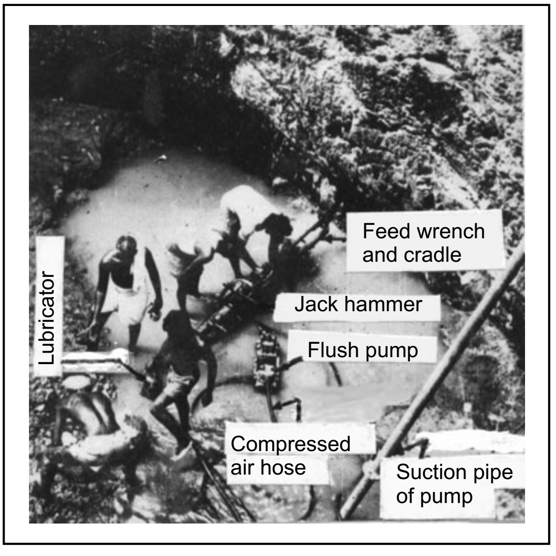

Fig. 3.24 Horizontal boring of a hard rock well in Veppani village, Chengelpet district, Tamil Nadu
Courtesy: Agricultural Engineering Department, Govt. of Tamil Nadu

length. The feed bench is installed horizontally at the point where the bore is to be made. The cradle moves along the feed cylinder with the retaining mechanism.

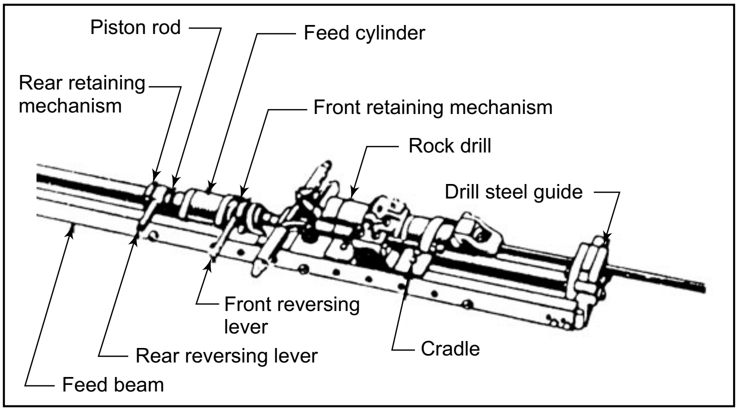

Fig. 3.25 Details of an auto-feed used in horizontal boring in open wells in hard rock formations
Adapted from: Atlas Copco (India) Pvt. Ltd., Mumbai

The operator opens the feed control placed on the cradle near the jack head of the rock drill, admitting air to the feed cylinder through the pipe. The piston rod is displaced outwards and the rear retaining mechanism engages the feed beam. The cradle advances, carrying the rock drill which is fed forward continuously. Feed direction is reversed, by means of reversing levers, for extraction of the drill steel. The control is managed by a separate throttle mounted on the cradle between the drill and feed cylinder. Thus, the drill and the auto-feed have separate air inlets.

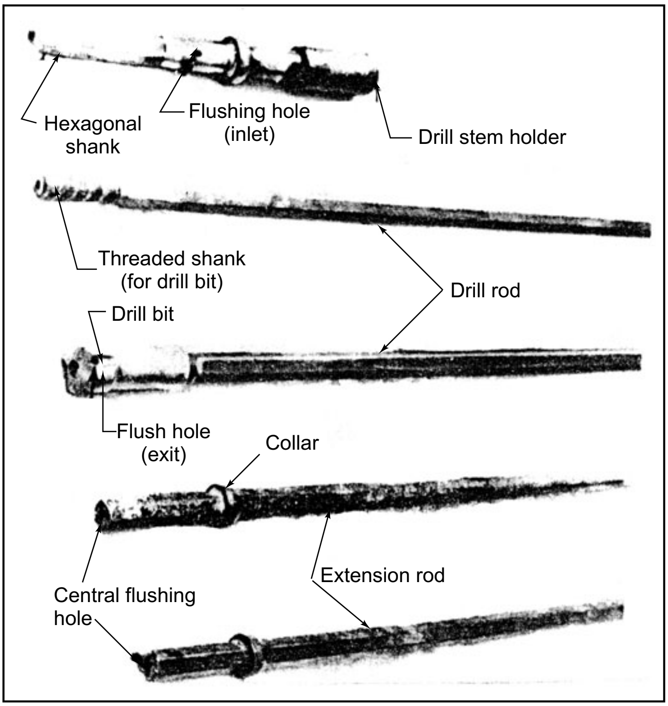

Fig. 3.26 Drill stem equipment for making horizontal and vertical bores in open wells

To enable the drill to proceed effectively, it is essential that the bottom of the hole is kept clean and the drill cuttings are continuously removed from the drill hole. This is done with a flushing medium—air, water or foam, which is forced into the bottom of the hole through a central flushing hole in the drill rod and flushing passage in the drill bit. The drill cuttings, comprising rock particles mixed with flushing medium, are forced out of the hole through the concentric space between the rod and the wall of the hole. Water flushing is usually used in horizontal drilling. The cuttings are bound effectively with water. Hence, a flush pump, operated by compressed air, forms an integral part of the horizontal well boring unit.

Air Line Accessories

Suitable accessories (Fig. 3.27) are essential for the economic operation of compressed air equipment. Pressure drop and leakage caused by the accessories of inadequate specifications may result in abnormally high operating costs. Most air tools are designated for a maximum working pressure of 6 to 7 kg/cm^2. Even a relatively small pressure drop may have a large effect on the power of the tool.

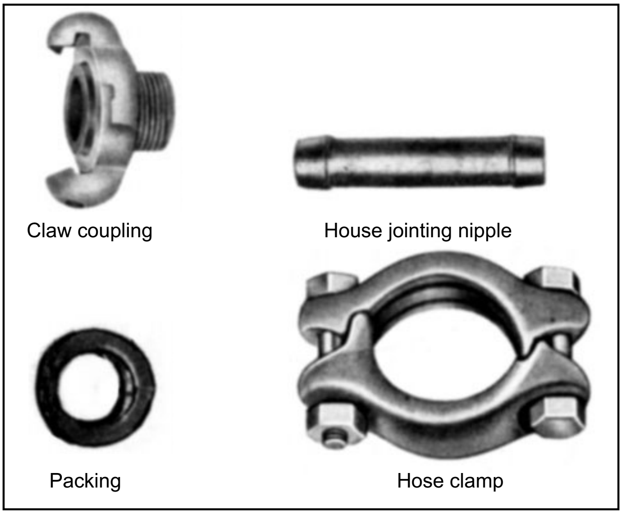

Fig. 3.27 Common accessories of compressed air line *Courtesy:* Atlas Copco (India) Pvt. Ltd., Mumbai

Compressed air hose. The compressed air hose is often subject to high stresses and must withstand rough handling. It should be weather-proof, oil resistant and capable of withstanding high pressure. Hence, it is essential to select the hose of the right specifications to withstand the pressure and other operating conditions.

Air line lubricator. Adequate lubrication is an essential requirement for the correct operation and maintenance of the rock drill and other compressed air tools. Air line lubricator (Fig. 3.28) is an oil reservoir in the air supply line ahead of the drill. The oiler is automatic, actuated by the flow of air operating the drill. Special grade oil is required for the air line lubricator.* While drilling, it should be ensured that the drill shank is getting adequate lubrication. With adequate oil in the lubricator, the drill shank will become dry within a short period after drilling is started. The oiler should be filled periodically so that the drill gets adequate lubrication throughout the

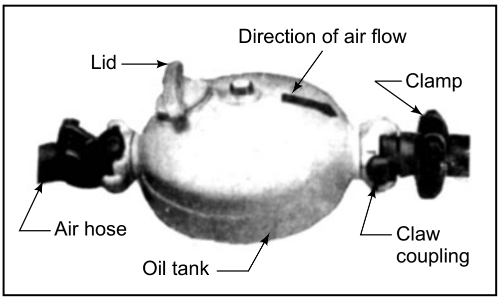

Fig. 3.28 Air line lubricator for compressed air tools *Adapted from:* Atlas Copco (India) Pvt. Ltd., Mumbai

* Some of the recommended oils for air lubrication:
INDIAN OIL—Servo Newm
CASTROL—Rock Drill Oil (light)
SHELL—Tonna Roil 41
CALTAX—Rock Drill Lubricant EP
HINDUSTAN PETROLEUM—Arox EP 65

drilling process. Lack of oil can cause complete breakage of the parts of the drill, including the air piston.

Claw coupling. Heavy duty claw couplings are used with compressed air hoses. It has an oil and temperature resistance seal made of synthetic rubber. The seal provides the required flexibility and easy coupling. Locking grooves in the coupling are machined to ensure good fit.

Hose nipples. Nipples are used for jointing hose with the clamp. They are made of hardened steel and are provided with locking edges at each end. They have a large bore size to avoid any appreciable pressure drop.

Hose clamps. Hose clamps are used to fit hose couplings and hose nipples. They are made of malleable cast iron and are shaped to provide a good joint. They are tightened by standard hexagonal bolts and nuts.

3.4.2 Rescheduling of Pumping Time

Studies at the Institute of Hydraulics and Hydrology, Poondi (Tamil Nadu), have shown that the gross yield of open wells in a given time period can be increased substantially by rescheduling the pumping time in suitable block periods. The drawdown and recuperation pattern of open wells in hard rock areas have specific characteristics. When a well is pumped to its fully capacity, the recuperation rate is high at the beginning, due to the steep hydraulic gradient. It gradually reduces, as the static water table depth approaches. Hence, intermittent pumping would result in a greater rate of recuperation or increase in yield of the well in a given time. Table 3.2 presents typical pumping test data for a well in a hard rock area, in which pumping was conducted in suitable block periods.

TABLE 3.2 Pumping test for an open well in a hard rock area, adoptingintermittent pumping at different block periods

	Depth of well, 6.5 m		Location: Village Acharapakkam, Dist. Chengelpet, Tamil Nadu				
Sl. no.	No. of block periods (h)	Pumping period (min)	Recuperation period (min)	No. of recuperations per day of 24 hrs	Total pumping time in a day (h)	Additional pumping time obtained (h)	% increase in yield
1	24	180	1260	1	3	—	—
2	1	30	30	24	12	9	300
3	2	51	69	12	10.2	7.2	240
4	3	69	111	8	9.2	6.2	206.6
5	4	81	159	6	8.1	5.1	170
6	6	105	255	4	7.0	4.0	133.3
7	8	129	351	3	6.45	3.45	115

Source: Anon. (1982)

Column 2 in Table 3.2 shows the block periods adopted for pumping and recuperation. For example, the data at serial no. 1 is for a block period of 24 h, in which pumping is possible for 3 h and the rest of the time (21 h) is allowed for recuperation. Serial no. 2 is for a 1-h block period comprising 30 min pumping and 30 min recuperation. Thus, there are 24 pumping periods and an equal number of recuperation periods in a day. This will provide for 12 h pumping, or an addition of 9 h in the total pumping time in a day. If the pump discharge does not vary appreciably, the total yield of the well could be assumed to increase 3 times. From a practical point of view, it may be difficult to have pumping periods at such short intervals. However, block periods of 3-8 h could easily be adopted. Possible increases in total pumping time by adopting 3, 6 and 8 h block periods are 206.6%, 133.3% and 115%, respectively, as compared to a single pumping in a day. In case of pumps operated by electric motors, the duration of the block period should suit the availability of electric power. Diesel pumps, however, have no such limitation.

3.4.3 Increasing Ground Water Recharge

Open wells usually derive their supplies from shallow water bearing formations. Hence, their yield capacity is proportional to the extent of ground water recharge in the area contributing the flow into the well. Any method of increasing ground water recharge will improve the performance of the well. Soil and water conservation measures, including land levelling, contour bunding and terracing, will greatly increase ground water recharge. The objective is to retard the rainfall runoff water and allow a longer time for infiltration. Construction of earth dykes or bunds downstream of the well will provide for the ponding of runoff water from the surrounding catchment, which eventually gets recharged into the ground water basin. Bunds are aligned along the contour. The size of the bund will depend on the amount of runoff to be intercepted. In cropped fields, this will depend on the extent of ponding that can be tolerated by the crop. It may often be necessary to provide an erosion-proof outlet (masonry structure or grassed outlet) for the safe disposal of excess runoff.

3.5 FAILURE OF OPEN WELLS DUE TO EXCESSIVE PUMPING

Pumps for open wells are selected to match the yield (recuperative yield/storage in a given time) of the well. When a pump is to be used continuously over long periods, the rate of recuperation of the well determines the design discharge of the pump. In case the storage accumulated over a period is to be pumped over a given time the pump discharge far exceeds the recuperative yield of well. The storage is pumped over a reasonable period, depending on the capacity of the water conveyance system and the required size of the irrigation stream. Creation of sudden drawdown due to excessive pumping rates, however, could result in the collapse of well lining in open wells in alluvial formations (Fig. 3.29).

3.6 SANITARY PROTECTION OF WELLS

Ground water, in its natural state, is usually of good sanitary quality, especially when aquifers are composed of sand. However, shallow ground water bodies, which are the main sources of domestic water supplies, have a high contamination potential when located in habitated areas. Often, these aquifers get seriously polluted, primarily with the liquid waste derived from sewage disposal systems, cesspools, poorly constructed septic tanks, soak pits attached to privies, manure pits, and industrial and agricultural waste-disposal systems.

A common source of pollution of ground water in rural areas is due to dumping of garbage and other pollutants in abandoned open wells. Improperly constructed or poorly located wells in these areas often serve as conduits for the migration of contaminants into the ground water system.

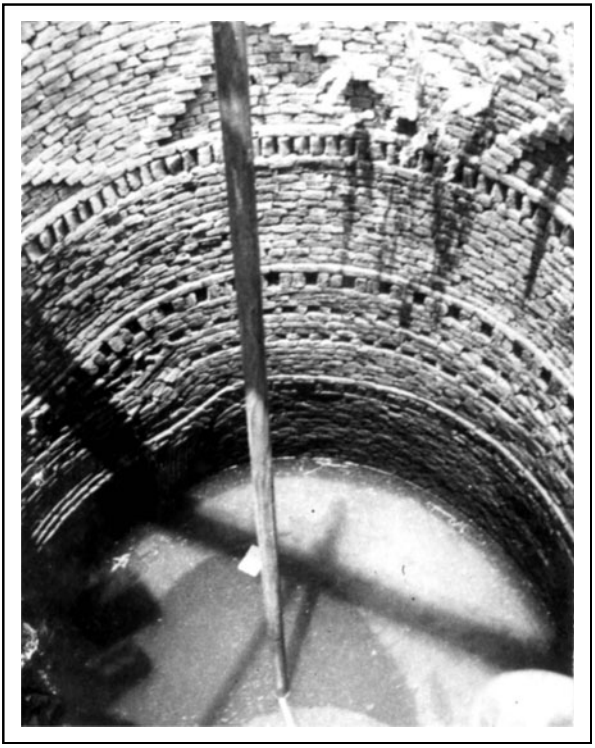

Fig. 3.29 Severe cave-in and deformation of well lining resulting from excessive rate of pumping from an open well in Kakkalore village, Dist. Chengalpet, Tamil Nadu. Proper regulation of the rate of pumping within the yield rate of the well is essential to maintain the stability of masonry lined open wells.

Courtesy: Institute of Hydraulics and Hydrology, Poondy, Tamil Nadu

Good well-construction practices and regulations protect the health of the community. With the large number of wells constructed every year for rural and urban water supplies, it has become essential to provide protective measures in well construction. The protective measures required for water supply wells vary with the physical surrounding and the type of geological formation.

3.6.1 Pollution Travel in Soils and Aquifers

Pollution, as applied to ground water supplies, may be defined as the impairment of water quality by chemicals or bacteria to cause hazards to public health or crop growth. A high degree of pollution is often termed as *contamination*. While bacterial contamination is harmful to human health and may carry some of the dreadful diseases, chemical contamination may adversely affect men, animals and crops. Shallow aquifers readily receive, store and transmit contaminants to downstream reaches which find entry into wells. Deep confined aquifers are usually unaffected by surface pollution sources. Wells tapping deep aquifers, should be sealed to prevent the entry of water from formations lying above the impermeable layer. Hard rock wells have high potential for contamination, since the contaminants pass easily through the crevices and fissures in the weathered formations (Fig. 3.30).

Fig. 3.30 An abandoned open well filled with garbage producing heavy pollution in the ground water in the surrounding region.
Courtesy: Institute of Hydraulics and Hydrology, Poonday, Tamil Nadu

All the water seeping into the ground is polluted to some degree. There is, however, a natural purifying action as the polluted water passes through the soil or sandy aquifer. The natural processes occurring in the soil or aquifer to purify water travelling through them comprise the following:

(i) Mechanical removal of micro-organisms and other suspended matter by *filtration*. Filtration is influenced by the relative sizes of the pore spaces in the soil and those of the micro-organisms and other filterable material. Finer soil particles and smaller pore spaces increase the effectiveness of filtration.

(ii) *Sedimentation*, or settling of the suspended particles. Sedimentation depends upon the size of the suspended particles and the velocity of water flowing through the pore spaces. Large size particles and low velocity of flow through the soil tend to improve the sedimentation process.

(iii) Natural *die-away* of bacteria in soils. Disease producing bacteria live only for limited periods of time outside their natural host, viz. man or animals. This contributes greatly to the self-purification of ground water during its movement and storage in sand and gravel aquifers.

The effect of filtration is almost absent in the flow of water through the crevices and fissures in hard rock formations. Thus, the microbiological quality of ground water in sand, gravel and other unconsolidated formations is superior to that in hard rock formations.

The processes of natural purification of ground water are more effective in the control of bacterial pollutants than chemical pollutants. Chemical pollutants last longer and travel faster in the soil than bacterial pollutants. Both the bacterial and the chemical pollutants in soils usually move downward from the source till it reaches the water table. It then flows along with the ground water. The downward flow of bacteria above the water table is usually limited to a depth of about 2 m.

Location and Design of Wells with Sanitary Protection

The presence and severity of bacterial and chemical contamination in a well depends on its location, design and construction. The following are the common sources of contamination entering a well:

(i) Seepage from sewage disposal areas, manure pits, privies, cesspools and graveyards (Fig. 3.31).
(ii) Spillage of polluted water from the washing of clothes and bathing areas.
(iii) Surface runoff entering a well at its top.
(iv) Introduction of contaminated buckets, utensils and ropes into a well by different users.

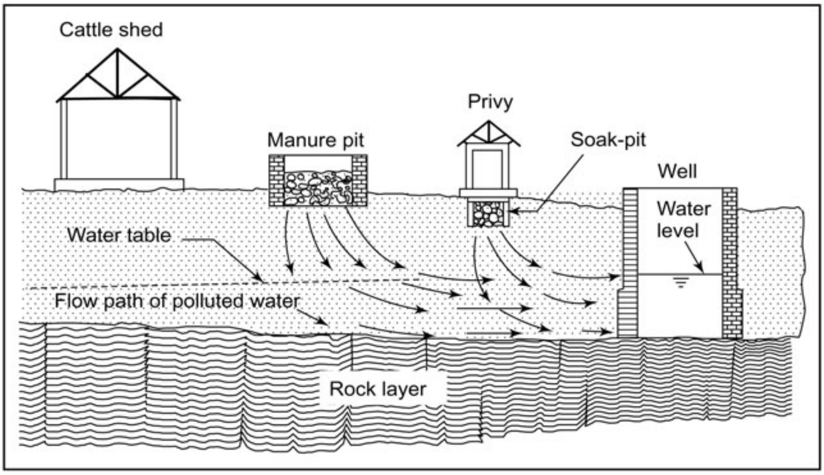

Fig. 3.31 Schematic sketch illustrating serious pollution of the water in a well located downstream of a cattle barn and privy

Well Location

Wells should be located on a higher ground than the surrounding sources of pollution. The ground surface in the immediate vicinity of a well should slope away from it and should be well drained. A special drainage system should be provided for the disposal of waste water from drinking water wells. A well, located downhill of a pollution source, should be placed at a reasonably safe distance away, depending on the pollution source and the soil conditions. The following are the minimum distances to be kept between a pollution source and a drinking water well:

Pollution source	Recommended minimum distance of well
Cast iron sewer with lead or mechanical joint	3 m
Septic tank or sewer of tightly jointed tile	15 m
Privy, manure pit, or drain field	22 m
Cesspool receiving raw sewage	30 m

Well Construction

The entry points for contaminants into a well are the open top end of the well and the annular space between the well steining and the surrounding subsoil formation. To prevent the entry of contaminated surface runoff into the well, the steining should extend at least 30 cm above the general level of the surrounding land surface. To prevent entry of contaminated water from around a well, a 10 cm thick water-tight concrete/brick/stone layer is laid, extending at least 60 cm all around the well. A drain pipe is provided for the effective disposal of spilled water (Fig. 3.32). The top 2 to 3 m of the well steining is made water-tight by laying the masonry in cement mortar and plastering or pointing. The bottom part of the steining is kept pervious by having sections laid without mortar, or providing *weep holes* in the well steining.

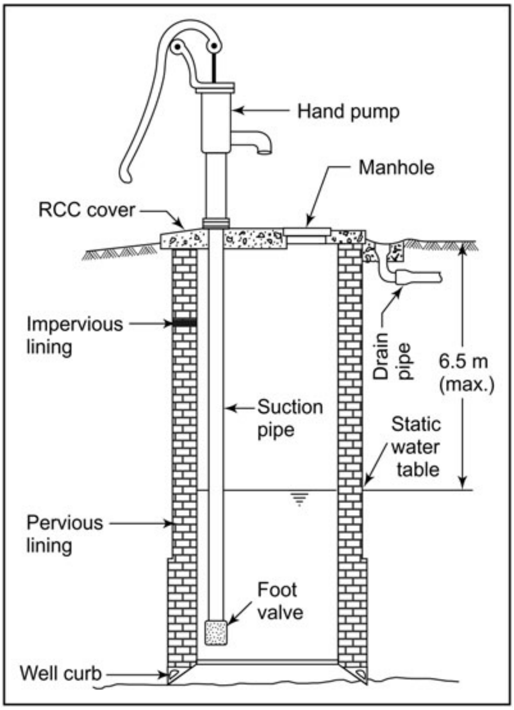

Fig. 3.32 A shallow dug well with provision for sanitary protection

It is a good practice to provide a reinforced concrete or brick-work cover on the top of open wells. The cover, when made of concrete, should be about 15 cm thick and adequately reinforced. It should project outside the well lining by about 5 cm and should slope towards the periphery. Provision is made in the well cover to install pumps and provide for inspection through a manhole provided with a suitable lid (Fig. 3.32). Contamination due to buckets and ropes introduced into wells can be eliminated by installing hand pumps or other types of pumps and providing a water-tight cover over the well.

Prolonged non-use of a water well creates conditions which lead to increased potential for contamination and accelerates deterioration. After abandonment, the well structure may become a subsurface conduit for adding contaminants to a fresh-water aquifer. When a well is abandoned, it should be ensured that the pump is removed and steps taken to prevent chances of pollution. Sometimes, an abandoned well is used as a receptacle for the disposal of waste, leading to severe pollution of the ground water in the neighbourhood. When an abandoned well is backfilled, care should be taken to restore, as far as possible, the geological conditions which existed before the well was constructed.

3.6.2 Disinfection of Wells

Disinfection is the final step in the completion of a water supply well. Its aim is the destruction of all disease-producing organisms (bacteria, protozoa and viruses) introduced into the well during construction. Entry of these organisms into the well can occur during the various operations in well construction, or through surface drainage into the well. All newly constructed wells used as a source of drinking water supply should, therefore, be disinfected. Wells should also be disinfected after each repair.

The well should be cleaned of foreign materials, such as oil, grease, etc. before the disinfectant is applied. The disinfectant used should be able to kill all pathogenic organisms. It should render the water neither toxic nor unpalatable. The action of the disinfectant, in terms of the killing of harmful organisms, is proportional to the duration of contact and concentration of the disinfecting agent. Disinfection is usually carried out by adding a strong solution of chlorine to the well. The water in the well is thoroughly agitated and allowed to stand for several hours, preferably overnight. The exposed surface inside the well, above the water level, is also washed with the disinfectant solution. Following this the well is pumped repeatedly to flush out the excess chlorine.

Chlorine is used for disinfection in the form of bleaching powder ($CaOCl_2$), calcium hypochlorite $Ca(OCl)_2$ or free chlorine. Chlorine available in bleaching powder varies from 33 to 39 per cent. In calcium hypochlorite it is about 70 per cent. The reaction with calcium hypochlorite is as follows:

$$Ca(OCl)_2 + H_2O \rightleftharpoons Ca^{++} + H_2O + 2OCl^- \tag{3.13}$$

$$H^+ + OCl^- \rightleftharpoons HOCl \tag{3.14}$$

If ammonia or organic nitrogen is present in water, they react with chlorine and hypochlorous acid to form monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3) as follows:

$$NH_3 + HOCl \longrightarrow NH_2\,Cl + H_2O \tag{3.15}$$

$$NH_2Cl + HOCl \longrightarrow NHCl_2 + H_2O \tag{3.16}$$

$$NHCl_2 + HOCl \longrightarrow NCl_3 + H_2O \tag{3.17}$$

The above reactions also depend on the pH value of water. Monochloramine and dichloramine are active disinfectants and are called *combined available chlorine*.

Liquid chlorine is chlorine gas which is compressed to the point at which it liquifies. It is available in cylinders. With the help of control valves and manometers, the dosage of chlorine can be adjusted. The reaction with chlorine is as follows:

$$Cl_2 + H_2O \rightleftharpoons HOCl + HCl \tag{3.18}$$

Hydrochloric acid is neutralized by the alkalinity in water and hypochlorous acid becomes dissociated. The quantities of HOCl (hypochlorous acid) and OCl^- ion depend upon the pH value. At pH 8.5, about 90 per cent of HOCl is ionised to hypochlorite ion. Cl_2 in the elemental form remains in water only for a short period. HOCl and OCl^- ion remain in water and are called *free available chlorine.* HOCl is a more effective disinfectant. In water having pH values ranging between 6 and 7.5, 40 to 50 per cent of the free available chlorine is in the form of HOCl. Soft water with high pH value is to be treated with higher doses of chlorine to compensate for the low disinfecting power of OCl^-.

Chlorine reacts with different substances, especially reducing agents as follows:

$$H_2S + 4Cl_2 + 4H_2O \rightleftharpoons H_2SO_4 + 8HCl \tag{3.19}$$

Organic compounds also react with chlorine, thus increasing its consumption.

Calcium hypochlorite is available in granular and tablet forms. It is fairly stable when dry, retaining about 90 per cent of its original chlorine content even after one year's storage. However, it loses its strength when moist and becomes corrosive. Hence, it should be stored under cool, dry conditions. Enough calcium hypochlorite is added to the water in the well to produce a strength of about 100 ppm by weight. This strength of the disinfectant, can be obtained by adding about 4 table spoons (heaped to capacity) to every 500 litres of water in the well. Usually a stock solution is made by mixing the chemical with a small amount of water to form a smooth paste and then adding more water and stirring the mixture thoroughly for 10 to 15 minutes before allowing to settle. The clear liquid is then poured into the well.

Sodium hypochlorite may be used in the absence of calcium hypochlorite. It is available in liquid form and has about 20 per cent available chlorine. A stock solution of equivalent strength to that made from calcium hypochlorite is prepared, as described in the previous paragraph and applied to the well.

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PROBLEMS

3.1 A well is to be constructed in a coarse sand formation. The anticipated discharge of the well is 15 m^3/h, under a depression head of 2 m. Determine the diameter of the well.

Ans. 3.1 m

3.2 A uniform thickness of steining is to be provided for an open well of diameter 3 m. Determine the theoretical as well as actual thickness of the well steining to be provided. Use the nomograph presented in Fig. 3.7. The depth of the well is 20 m.

Ans. Theoretical thickness = 45 cm, Actual thickness = 46 cm

3.3 Determine the depth and cross-sectional area of steel reinforcement required for a RCC well curb of an open well, with an inner diameter of 4 m. The thickness of steining at the bottom is 34.5 cm. The load of masonry is 75 kg/cm length.

Ans. Depth = 70 cm, A_{st} = 18.8 cm^2

3.4 Determine the depth of a wooden well curb for an open well, with an inner diameter of 3 m and 23 cm thickness of steining at the bottom. The load of masonry is 70 kg/cm length.

Ans. Depth = 42 cm

SHORT QUESTIONS

I. State True (T) or False (F).

1. Open wells are unsuited to shallow and low-yield aquifers.
2. Open wells are used to tap ground water in hard rock areas.
3. Open wells in hard rock formation are usually circular in cross section.
4. There is no need of installation of well screens in an open well.
5. Weep holes are provided in lined open wells for the lateral entry of water.
6. Vertical bores are provided at the bottom of dug wells to augment their yields.
7. Dug-cum-bore-wells are hydraulically inferior to ordinary dug wells.
8. In case of open wells, the critical velocity of entry of water is usually assumed as 5 cm/min.
9. In case of masonry dug well, the same thickness of steining is adopted for the whole depth.
10. Well curb is used for sinking of open wells.

11. The well steining is constructed on the well curb.
12. The width of well curb is less than the thickness of the steining at the bottom of the well.
13. For same spacing between wells, the effect of mutual interference between adjacent well will be more in alluvial formations than in hard rock formations.
14. In dug-cum-bore wells the boring is carried out with reverse rotary drilling.
15. The quicksand problem occurs due to saturated hydraulic pressure gradient.
16. The flow of quick sand in open wells can be prevented by removing the material and keeping the excavation partially full of water.
17. The weathered zone is important as far as occurrence of ground water is concerned.
18. The chances of striking water within a dyke are more.
19. Dykes act as a barriers to ground water movement.
20. Dykes stop and/or change the lateral movement of ground water.
21. On the upstream side of a dyke, one may get low yielding wells.
22. Boring in dug wells in hard rock area is carried out by percussion drilling rigs.
23. Bore wells are highly suitable for hard rock areas.
24. The longer side of rectangular well should be parallel to the direction of fracture system to ensure better yield.
25. A dug well should not extend beyond weathered zone.
26. Blasting gelatine was discovered by Alfred Nobel.
27. The yield of an open well can be increased by drilling horizontal bores above the water table.
28. Intermittent pumping results in a greater rate of recuperation.
29. Finer soil particles and smaller pore spaces decrease the effectiveness of filtration.
30. The ground surface in the immediate vicinity of a well should slope towards it.
31. An open well may become dry if a bore well is drilled nearby and pumped continuously.
32. Wells are spaced far apart in hard rocks than in alluvial formations.

Ans. True: 2, 4, 5, 6, 10, 11, 13, 15, 16, 17, 19, 20, 22, 25, 26, 28, 31.

II. Select the correct answer.

1. In unconsolidated formation, the cross-section of open well is generally
   (a) rectangular (b) circular
   (c) triangular (d) both rectangular and circular
2. The depth of open wells in alluvial formation below the water table in the dry season is
   (a) 7 to 10 m (b) 15 m
   (c) 20 m (d) 15 to 20 m
3. In a brick-lined open well, the minimum thickness of steining should be
   (a) 12 cm (b) 23 cm
   (c) 28 cm (d) 34.5 cm
4. The minimum width of the well curb should be more than the thickness of steining at the bottom of the well by
   (a) 5 cm (b) 10 cm
   (c) 15 cm (d) 20 cm

5. In order to avoid the mutual interference between adjacent open wells in alluvial formation, spacing between wells should be
   (a) 20 – 25 m (b) 25 – 50 m
   (c) 50 – 75 m (d) 75 – 100 m
6. Weep holes in well lining of open wells are provided
   (a) to strengthen the wall (b) to permit entry of water in to the well
   (c) for sinking of the well (d) to sustain lateral earth pressure
7. The permissible critical velocity of flow in masonry open wells in alluvial formation is
   (a) 2.5 cm/min (b) 5.0 cm/min
   (c) 7.5 cm/min (d) 10.0 cm/min
8. Diameter of dug well in unconsolidated formation varies from
   (a) 2 to 5 m (b) 5 to 8 m
   (c) 8 to 10 m (d) 10 to 15 m
9. The predominant material in blasting explosives is
   (a) gunpowder (b) gelatin
   (c) nitro-glycerin (d) nitro-cotton
10. The depth of shot hole commonly used in rock blasting in open well is
    (a) 0.6 m (b) 1.2 m
    (c) 2.2 m (d) 3.2 m
11. The downward flow of bacteria above the water table is limited to a depth of
    (a) 1 m (b) 2 m
    (c) 3 m (d) 4 m

Ans. 1(b) 2 (a) 3 (b) 4 (a) 5 (d) 6 (b) 7 (c) 8 (a)
9 (c) 10 (b) 11 (b)

4

Tube Wells and Their Design

A large number of tube wells are installed every year for irrigation, drinking water supply and industries. The type of tube well to be constructed depends on the characteristics of the ground water formation, intended use of the well and financial resources of the well owner. Irrespective of the type of well, it must be designed properly to obtain high yields and efficiency as well as long and trouble-free service.

4.1 TYPES OF TUBE WELLS

Tube wells are classified on the basis of the entry of water into the well, the method of construction, the depth and the type of aquifer tapped. These are listed below:

1. Entry of water
   (a) Screen wells
      (i) Strainer wells
      (ii) Slotted pipe gravel pack wells
   (b) Cavity wells
2. Method of construction
   (a) Drilled wells
   (b) Driven wells
   (c) Jetted wells
3. Depth
   (a) Shallow wells
   (b) Deep wells
4. Type of aquifer
   (a) Water table wells
   (b) Semi-artesian wells
   (c) Artesian wells
   (d) Bore wells in hard rock areas
   (e) Skimming wells

4.1.1 Based on Entry of Water

Tube wells are classified as screen wells or cavity wells on the basis of the entry of water from the aquifer into the well.

Screen Wells

Tube wells using screens to permit the entry of water from the surrounding aquifer may either be strainer wells or slotted pipe gravel-pack wells. Plain pipes and screens are lowered into the bore hole. The screens are located opposite the water bearing strata. A bail plug is provided at the bottom of the pipe and strainer assembly.

The strainer wells are usually drilled with percussion rigs. The annular space between the tube well assembly and the walls of the bore gets filled with natural formation material when the casing is taken out. The well screen is designed to suit the aquifer material encountered. These wells are generally limited to shallow depths.

The slotted-pipe gravel-packed well is a development of the strainer well in which shrouding (gravel-packing) is done around the slotted-pipe screen (Fig. 4.1).

Several types of well screens are used to suit the specific requirements of the aquifer and economic status of the farmer. Johnson (1966), listed the following as the desirable features for a properly designed well screen:

(i) Openings in the form of slots which are continuous and uninterrupted around the circumference of the screen.
(ii) Close spacing of slot openings to provide the maximum percentage of open area.
(iii) V-shaped slot openings that widen inward.
(iv) Single metal construction to avoid galvanic corrosion.
(v) Adaptability to different ground water and aquifer conditions by the use of various materials.
(vi) Maximum open area consistent with adequate strength.
(vii) Ample strength to resist the force to which the screen may be subjected during and after installation.
(viii) Full series of accessories to facilitate screen installation and well completion operations.

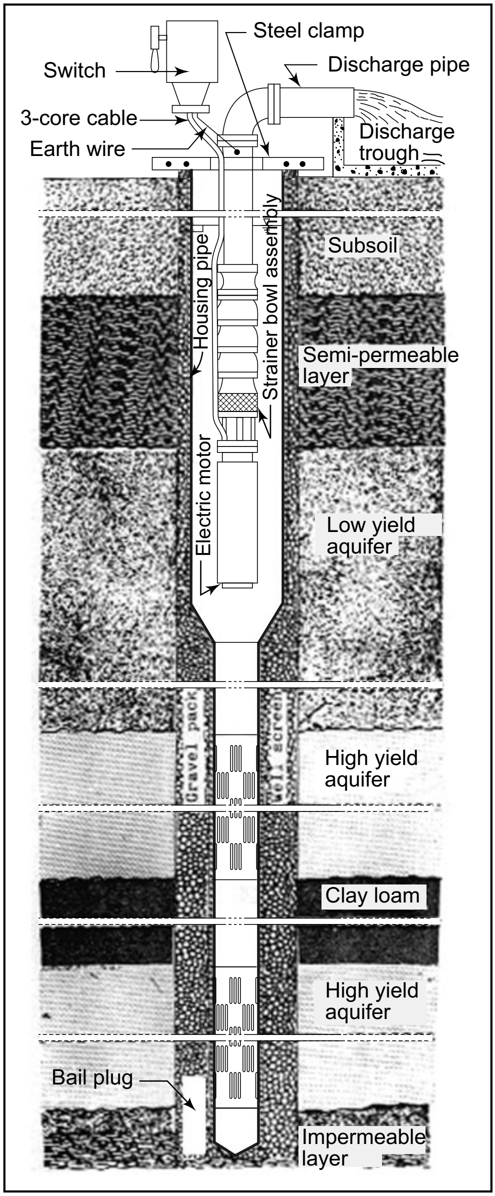


Fig. 4.1 Arrangement of tube well assembly, gravel pack and a submersible pump in a deep tube well (Sectional view). Note that the well screens are located against the water bearing formations and blind pipes against non-water bearing layers

Strainer-Type Well Screens

Strainer-type screens are suitable in water-bearing formations which mainly comprise coarse sand and gravel particles. Such formations are encountered in alluvial plains, coastal alluvium, and other areas adjoining river beds. The principle of this type of tube well is to obtain the water supply from the aquifer through a screen with narrow or very small openings. Sand particles larger in size than the opening cannot enter the tube well. The strainers are located against one or more water bearing layers. Strainer-type well screens may be either continuous-slot type, louver type, rope-wound strainers or pipe-base strainers with fine-mesh net envelope.

Continuous-Slot-Type Well Screen

Continuous-slot screens comprise wire and rope wound round a suitable frame made of rods or bars of iron or other materials. It is usually made by winding cold-drawn wire, approximately triangular in cross-section, spirally around a circular array of longitudinal rods (Fig. 4.2). At each point where the wire crosses a rod, the two are securely jointed. The well loss is much lower as compared to the slotted-pipe well screen (Fig. 4.3). The inwardly widening slots do not allow any particle to struck inside the slot and cause clogging. Thus the slots are non-clogging.

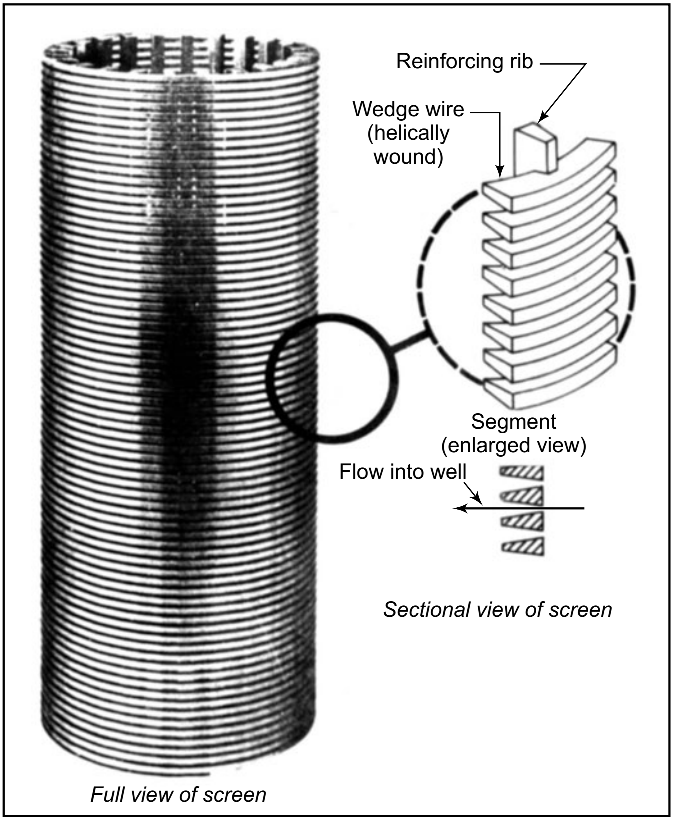


Fig. 4.2 Details of continuous-slot wedge-wire well screen
Adapted from: Surescreen Manufacturing Co. Pvt. Ltd., Zillmere, Brisbane, Australia

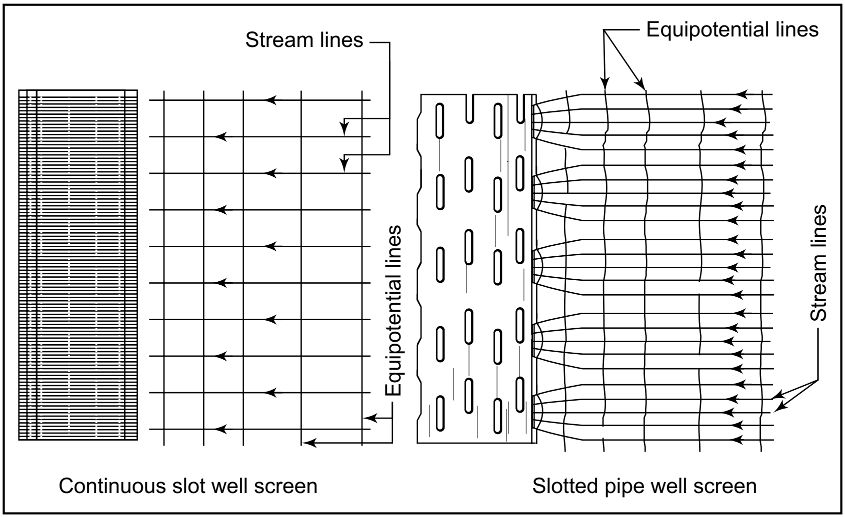


Fig. 4.3 Flow nets around continuous slot and slotted type well screens. Note the convergence of stream lines in flow into slotted pipes resulting in higher well loss
Adapted from: Surescreen Group of Companies, Zillmere Brisbane, Australia

Louver-Type Screen

Louver or shutter-type well screens have openings which are rows of louvers. The openings may be oriented either at right angles or parallel to the axis of the screen. They are produced in the wall of a welded tube by stamping process.

The continuous-slot and louver-type screens, though more efficient hydraulically, have not become popular in developing countries due to their high cost.

In India, most strainer wells are shallow tube wells, drilled by the percussion method (hand boring or mechanically operated cable-tool method). The strainers consist of rope or strands of nylon fibre wound round steel or bamboo frames. Agricultural strainers, comprising brass wire netting wrapped on perforated pipe, are also used, though they are not very common. The use of PVC strainers comprising nylon mesh net wrapped on perforated rigid PVC pipe is very popular in shallow tube wells.

Coir-Rope Strainer

The coir-rope strainer is a low-cost screen for shallow tube wells (Fig. 4.4). It is formed by winding a coir chord of 3-5 mm diameter spirally around a circular array of mild-steel longitudinal rods or bars. The frame is strengthened at suitable intervals with iron rings of 1 cm × 3 mm cross-section. One end of the longitudinal rods is rivetted or welded to mild-steel pipe sockets (Fig. 4.4), which are threaded. The other end is welded to a threaded pipe ring which can be fitted to the socket end of the preceding screen section. Hence, each length of the strainer can be joined to the next. The entire surface of the coir acts as a screen, allowing water to enter into it and at the same time preventing the entry of sand.

The main limitation of a coir strainer is its short life of about 3-5 years. The chief cause of its failure is the rusting of iron bars/strips of the supporting frame. This weakens the strength of the coir string at the contact points. Coating the iron frame with bitumen enhances the life of the strainer. Another cause of failure is the loosening of the coir string, which expands on wetting. Winding the string under a suitable tension increases the life of the coir screen. Synthetic fibre rope (nylon rope), when used in place of coir, will increase the durability of the strainer considerably.

The coir-rope strainer cannot withstand the high pressure developed during the development of tube wells by an air compressor. Therefore, such wells can be developed only by pumps.

In spite of the above limitations, the coir strainer is popular in shallow tube wells in deltaic regions of India, because of its low cost.

Bamboo Strainer

The bamboo strainer is essentially a coir rope strainer with the longitudinal members of the supporting frame made of bamboo strips instead of steel rods (Fig. 4.5). To make the strainer, bamboo strips are laid lengthwise, fixed on mild-steel rings of 10-12 cm diameter placed at about 30 cm intervals. Coir rope is wound around the cylindrical frame. Originally developed in Bihar, bamboo strainers have become popular as a low-cost material for shallow tube wells, especially in the Gangetic plains of Bihar and West Bengal. The adaptability of bamboo strainers is the same as that of an ordinary coir strainer. However, the durability of bamboo strainer is significantly reduced by micro-organisms, such as fungi and termites. The life of bamboo strainer can be increased by coating the bamboo with epoxy, tar or bituminous paint. The average life of bamboo strainer is about 5 to 6 years (Jha, 2004).

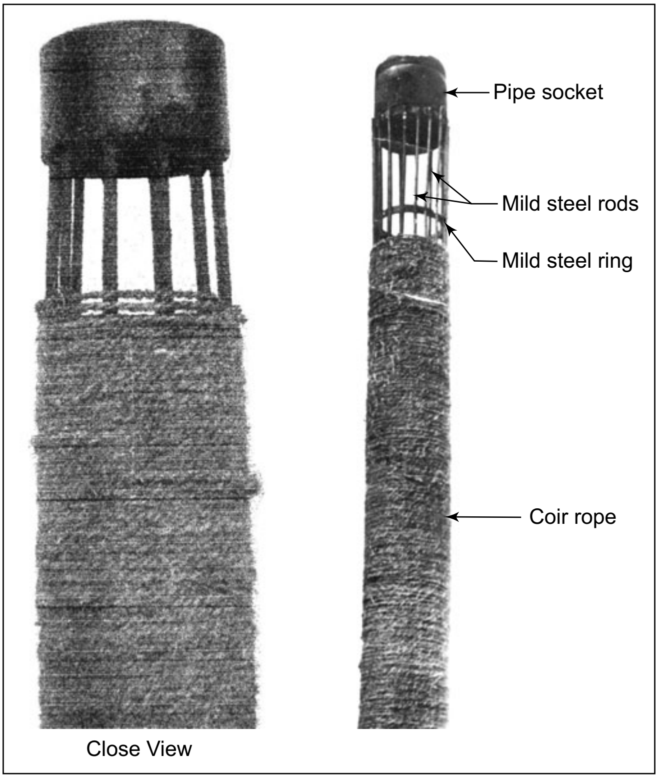


Fig. 4.4 Coir rope strainer with mild steel rod frame

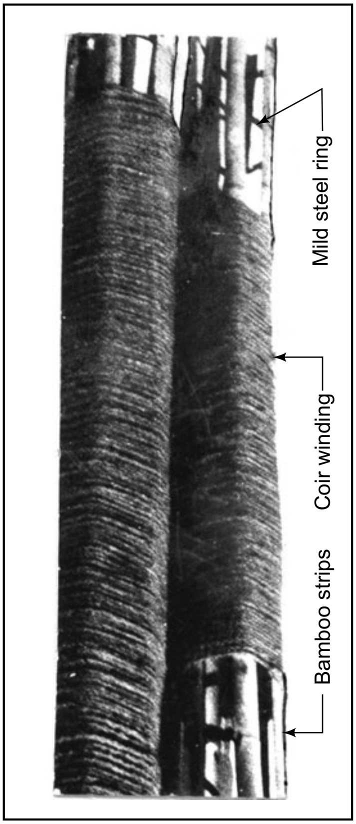


Fig. 4.5 Coir rope strainer with bamboo frame (partially exposed view)

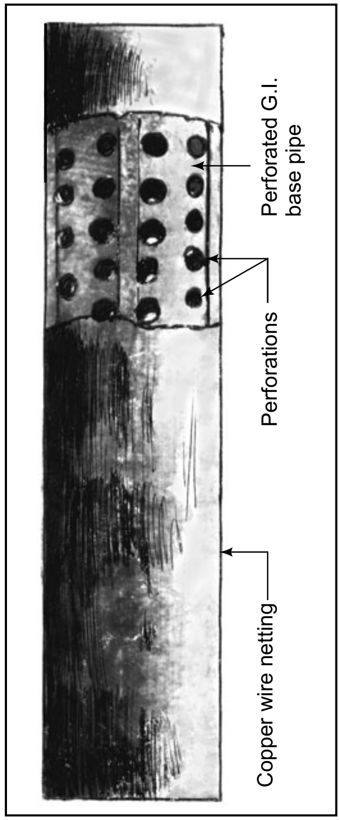


Fig. 4.6 Agricultural strainer (partially exposed view)

Agricultural Strainers

Various designs of agricultural strainers are available in the market. The most commonly used design of agricultural strainer consists of a perforated galvanised iron pipe on which iron hoops or strips of 1 cm width and 3 mm thickness are welded. The perforations are round and made with a drilling machine. They are so arranged that these strips do not cover the perforated portions. Copper netting is wrapped and soldered over the iron hoops and strips (Fig. 4.6).

The type of copper mesh used depends upon the type of sand strata encountered along the bore. Usually 3 types of copper nettings, suitable for fine, medium and coarse strata, are available in the market. In this design, the wire netting is not in direct contact with the perforated tube over which it is wrapped. Hence, the area of perforations is not decreased by the copper netting in front of the perforations. The above arrangement provides better hydraulic efficiency.

The adaptability of the agricultural strainer is almost the same as that of the coir strainer. It could, however, be used for comparatively deeper wells. Its performance is better than the coir strainers, in case of formations having fine silt particles. It is more expensive than coir or bamboo strainers, but is more durable (about 10 years).

The disadvantage of the agricultural strainer is that it usually involves a bi-metallic construction (the pipe base of steel and the outer jacket of brass or bronze) which results in electrolytic action and corrosion of the steel pipe. One way to prevent electrolytic action is to make the pipe base of the same metal as the screen jacket, but this would considerably increase the cost.

Pipes made from other materials, such as ceramics and asbestos cement, have been used as perforated castings. But these have the disadvantage that they are very heavy and difficult to install. Moreover, the percentage open area of such screens is low. Sometimes cage-type screens are used. In this case, the outer jacket is mounted on a frame of longitudinal strips, stiffened at intervals with rings/hoops, instead of perforated pipe. However, this design has very limited application because of low strength.

In developed countries, the strainer corresponding to the agricultural strainer is a pipe-base well screen (Fig. 4.7), which consists of a slotted PVC pipe with vertical slots. A continuous slot screen jacket is mounted on the perforated pipe. The jacket is made by winding triangular PVC wire directly on the slotted pipe. The screen is provided with pipe sockets at the ends.

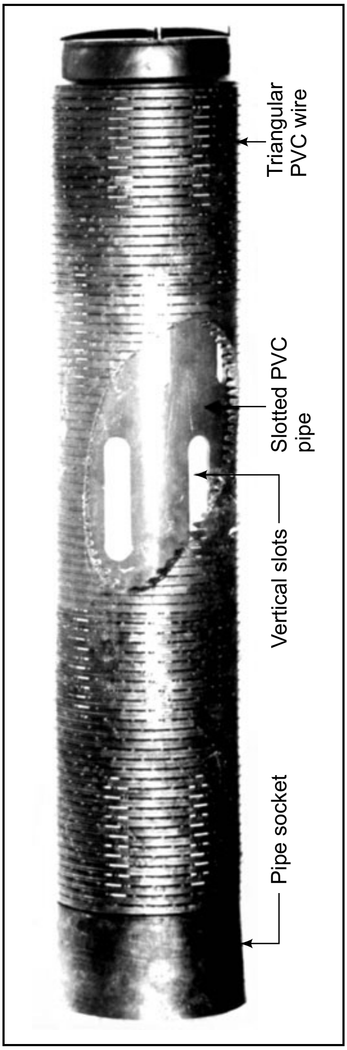


Fig. 4.7 Partially exposed view of a PVC slotted pipe-base continuous slot well screen. Ring appertures shown are mixed, illustrating possible alternate settings. *Courtesy:* John Warwick, Woolooware

Slotted-Pipe Well Screens

Slotted pipe well screens are usually used with gravel pack around them, primarily to prevent the entry of fine sand. Such screens are adopted in case of aquifer formations having a mixture of fine and coarse particles, or in case of relatively deeper wells. Various designs of slotted-pipe screens (Figs. 4.8 and 4.9) are available in the market.

Mild Steel Slotted-Pipe Well Screens

Mild steel slotted-pipe well screens (Fig. 4.8) are usually made of medium- and heavy-duty mild steel pipes. The shape and size of the slot should be such that the aquifer material or gravel is not allowed to block the open area of the screen. The total open area varies from 15 to 22 per cent of the surface area of the pipe. Based on the sieve analysis of the aquifer material, the size of the slot is determined such that the finer fractions of the formation are removed during the development stage of the tube well and the coarser fractions are retained around the well screen. The slots should not be wide enough to cause the entry of gravel and consequent plugging of the screen. The standard slot sizes commonly used in India are 1.6 and 3.2 mm wide and 10 cm long. The minimum spacing between slots is 3 mm. The slots are so arranged as to obtain an even distribution of flow over the entire periphery of the screen. They are distributed in groups of 3 or 4 and arranged so that the slots of one group are not in line with those of the adjacent row, in order to provide adequate strength to the well screen. A typical view of the arrangement of slots is shown in Fig. 4.8.

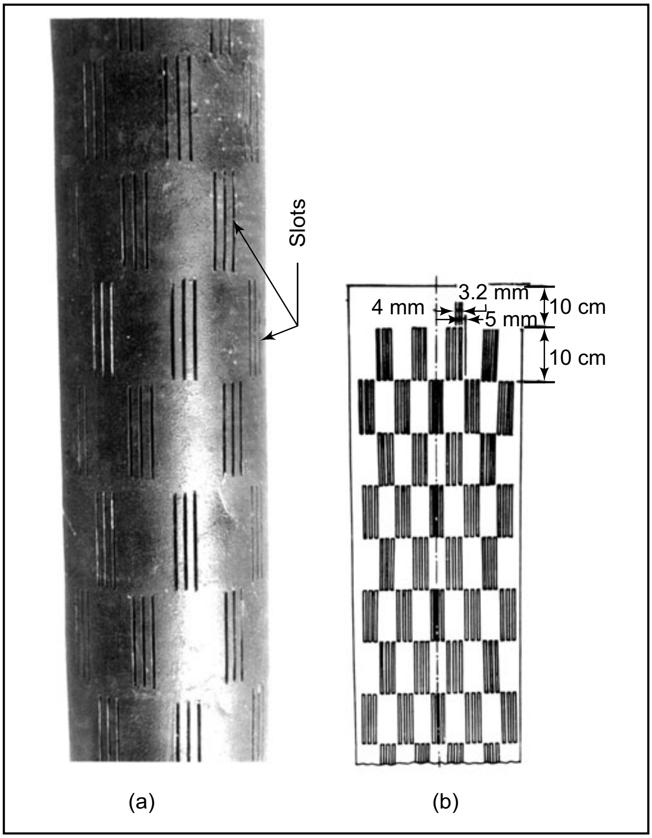


Fig. 4.8 Mild steel slotted pipe well screen: (a) General view, (b) Layout of slots as per Indian Standard specifications IS 8110-2000

The slotted pipe is threaded at both ends. The bottom end of the slotted pipe is fitted with a blind pipe 1.25 m long with a cap called a bail plug at the bottom. The bail plug has an 'eye' fixed inside in order to facilitate the extraction of the tube well assembly in case of failure.

Slotted Pipes with Pre-Pack Filters

Pre-pack filters have their gravel-pack cast on slotted pipes. In the manufacture of pre-pack filters, graded hard gravel grains are coated and bonded together with water proof chemicals, over the outer surface of a slotted pipe. The gravel is fixed loose, providing a high value of permeability. The gravel size used varies, depending on the grain-size distribution of the aquifer. Pre-pack filters are suitable for shallow and medium deep tube wells in areas with aquifers composed of fine sand, coarse sand and gravel. It is claimed that pre-packing provides economy in the quantity of gravel required, protects against dislodging of the gravel envelope, and significantly increase the collapse and tensile strength.

Brass Screens and Stainless Steel Screens

Brass screens (Fig. 4.9) and stainless steel screens are the most expensive well screens. Brass screens are usually used in tube wells for drinking water supply. Such screens are preferred over mild steel slotted pipes for their longer life, protection against incrustation and corrosion and contamination of water due to rusting. They are fabricated from brass/stainless steel sheets, about 4 mm thick. Brass sheets are an alloy of copper, zinc and lead. The ratio of copper, zinc and lead are generally 60 per cent, 38.75 per cent and 1.25 per cent, respectively. The slots are made as per the design of the well screen (Sec. 4.4.5). The slotted sheet is rolled and welded into a tube. The ends of the tube lengths (unslotted) are provided with outer threads for joining the tubes through a socket. Screens with different slot sizes and diameters are commercially available, and the size required is selected to suit the design and the particle-size distribution of the aquifer.

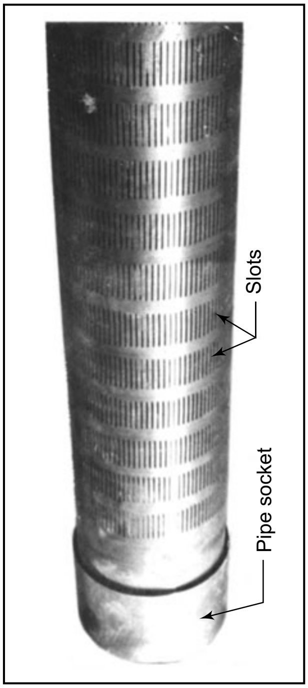


Fig. 4.9 Brass screen with slots

Rigid PVC Screens

Rigid PVC well screens are discussed in Sec. 4.3.

Cavity Tube Wells

A cavity well (Fig. 4.10) is a shallow tube well drilled in an alluvial formation. It does not have a strainer, but draws water through the bottom of the well pipe. The well casing rests on a thick and impervious layer lying above the water bearing formation. Cavity wells are very economical and can be adopted where the ground strata permits its construction.

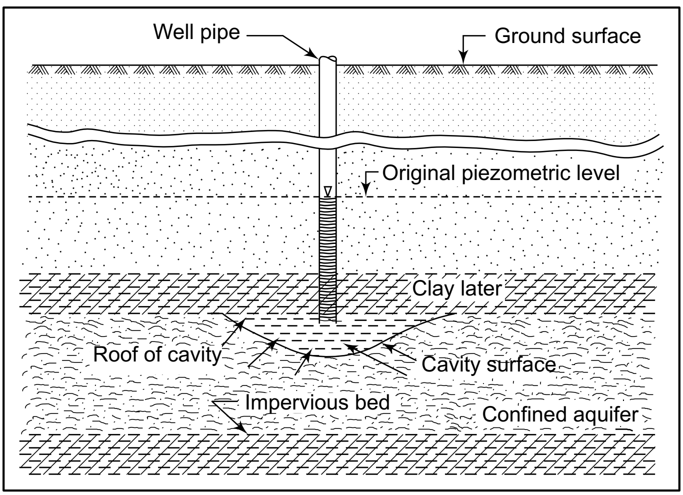


Fig. 4.10 Schematic sketch of a cavity well. (Anjaneyulu, 1972)

An essential requirement for a cavity well is that it should have a strong and dependable roof. The stratum immediately on top of the water-bearing layer, in which the cavity is to be developed, is known as the roof of the cavity. If it is a thick layer of clay, conglomerate or stone, it is not likely to collapse when water is pumped out of the cavity and is, therefore, considered a satisfactory roof. On the other hand, if the stratum is thin, friable or sandy, it is very likely to fall down or cave in, and the cavity well will fail.

A quick method of determining whether the clay forming a roof is suitable for a cavity well, is to take a lump of the clay and put it in a glass of clear water. If the clay disintegrates quickly, it is an indication that the roof is not suitable for a cavity well. On the other hand, if the clay does not disintegrate or dissolve in water the roof may be taken to be satisfactory, provided it is of sufficient thickness. It is difficult to specify exactly the thickness of clay stratum which will act as the roof of the cavity. A thickness of about 3 m is usually recommended. However, successful cavity wells have been developed even with a clay stratum as thin as one m. Much depends upon the exact nature and location of the impermeable stratum over the cavity.

Drilling is started at the correct site for a cavity well. The well is drilled past the impermeable roof to reach the confined aquifer. A cavity is formed in the water bearing sand stratum which is immediately below the roof and developed by drawing out the fine sand from around the bottom of the pipe. The cavity acts as a miniature reservoir for pumping.

For constructing a cavity well, drilling is carried out in the same way as in a strainer-type well, but the bailer (or sand pump) has to be operated slightly ahead of the cutting shoe of the casing pipe. Immediately after the bailer penetrates the sand layer in which the cavity is to be formed, the load on the casing pipe is removed so that the pipe will sink no further. The end of the cutting shoe of the casing pipe is left about 1 m above the bottom of the clay layer. Before using any mechanical equipment to form the cavity, a sand pump or bailer should be repeatedly operated and as much sand as possible removed. More sand has to be removed by developing the well, in order to form a suitable cavity. This is usually done by a centrifugal pump.

Boulder Wells

Boulder wells (Fig. 4.11) are like cavity wells, in that the necessity for a hard, stable stratum for roof formation is partly dispensed with. No screen is used. The necessary conditions for such wells, as the name implies, is the availability of a reasonably thick aquifer, containing boulder, gravel and coarse sand, about 5 m thick. When such a stratum is encountered, the open end of the boring pipe, is extracted to about 3/4th the depth of the water bearing boulder stratum, and the well is gradually developed, as in the case of a cavity well. Gradually, a cage of boulders and gravel is formed around the open bottom of the boring pipe from where some of the sand and gravel have been drawn out during the process of development.

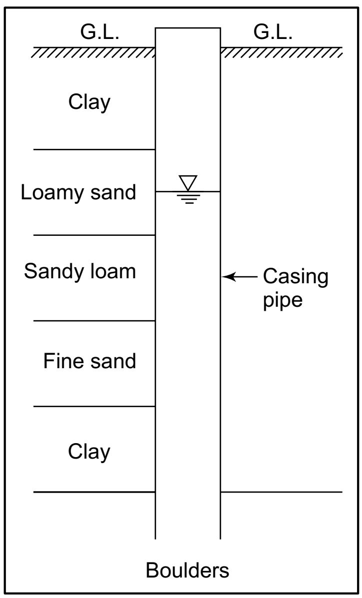


Fig. 4.11 Boulder well location

The development of boulder wells is carried out in stages. Each development operation is followed by raising the boring pipe by about 50 cm. Before the boring pipe is lifted, it should be ensured that the well is fully developed. While the development and lifting of the pipe is going on, the increase or decrease in discharge of the well should be observed. When the discharge is increasing, the process of lifting the pipe and development is continued to a total depth of about 2 m. However, if the discharge starts decreasing or there is no increase, further lifting should be stopped without satisfying the usual requirement of 2 m. The boring pipe left in the formation becomes the tube well casing pipe. It has been observed that the discharge from a boulder well is usually quite clear and the well yield in some cases is greater than that of a cavity well with the same size of pipe and in the same formation.

4.1.2 Based on the Method of Construction

Under this classification wells are grouped according to their method of construction. They are drilled wells, driven wells and jetted wells (Ch. 5).

Drilled Tube Wells

Drilled wells are constructed by making bore holes, using percussion and rotary drilling methods. Plain pipes and screens are lowered into the bore hole. Tube well construction involves drilling the bore hole, installing the casing and well screen, and developing the well to ensure sand-free operation at maximum yield. Where artificial gravel packing is called for, it is considered part of the well screen installation. All the wells discussed under the earlier classification, like strainer wells and slotted-pipe gravel-packed wells, are drilled wells.

Driven Tube Wells

A driven well consists of a pipe and well point which are forced into the water-bearing formation by driving with a wooden maul, drop hammer or other suitable means. Driven tube wells usually vary from 3-7.5 cm in diameter. They develop small yields and their construction is limited to shallow depths in soft unconsolidated formations free from boulders and other obstructions. They are commonly used for domestic water supply.

Jetted Tube Wells

A jetted tube well is constructed with hand-operated equipment or power-driven machines, depending upon the type of formation and the size and depth of the well. A hole in the ground is made by the cutting action of a stream of water. The water is pumped into the well through a pipe of small diameter. It is forced against the bottom of the hole through the nozzles of a jetting bit. The hole is cased to prevent a cave-in.

After the hole has been jetted down to the desired depth, the well assembly, consisting of plain pipes and screen, is lowered and the outer casing pulled out. Jetted tube wells have small yields and their construction is possible only in unconsolidated formations.

4.1.3 Based on Depth

Tube wells are classified as shallow or deep tube wells on the basis of their depth.

Shallow Tube Wells

Shallow tube wells are of low capacity. The average depth of the well is usually less than 35 m. Cavity tube wells and strainer tube wells with coir strainers generally fall in this category. The latter usually tap only the unconfined aquifer.

Deep Tube Wells

Deep tube wells are wells of high capacity, tapping more than one aquifer. Their depth usually ranges from 60-300 m. In India, most deep tube wells are state-owned. Farmers having large holdings also have deep tube wells. Deep tube wells may be strainer wells or gravel-pack wells, depending upon the characteristics of the aquifer formation.

4.1.4 Based on Aquifer Characteristics

Tube wells under this category are classified as water table wells, semi-artesian wells, artesian wells and hard rock bore wells. The classification is based on the location of the well and the characteristics of the aquifer. Wells may be defined as water table or artesian wells, depending upon whether they tap a water table aquifer or an artesian aquifer. Artesian wells are further classified as semi-artesian wells and flowing artesian wells. Tube wells bored in hard rock formations are classified as hard rock bore wells.

Water Table Wells

These are installed in unconfined aquifers which are under water table conditions, i.e. the water level is not under pressure. Generally, shallow tube wells fall under this category.

Semi-Artesian Wells

Semi-artesian wells are installed under semi-artesian conditions of aquifer. The water is under pressure, but not so high as to flow out of the well.

Artesian Wells

A flowing well gets its supply from an aquifer where the water is under such high pressure that it overflows at the top (Fig. 4.12). The well is so named because the initial knowledge about such wells was derived from Artois in France. The static water level in this case is above the ground and can be measured within the well casing, if the pipe is extended high enough so that the flow does not occur. Alternatively, flow can be contained by capping the well casing, after which the shut-in head can be measured with a pressure gauge.

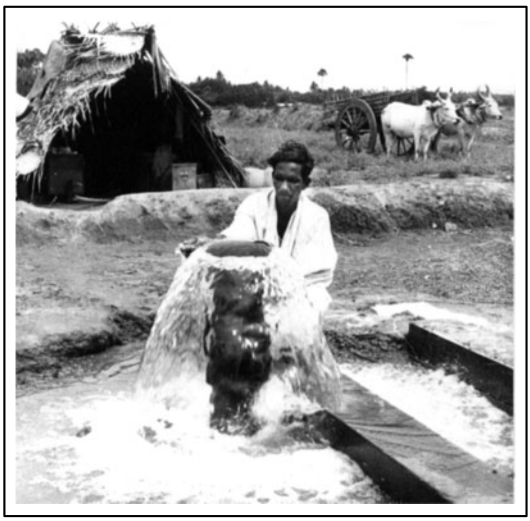


Fig. 4.12 A flowing artesian well near Thanjavur, Tamil Nadu

Bore Wells in Hard Rock Areas

Tube wells in hard rock areas are called bore wells because the bore hole is able to hold on its own for most of its depth and the tube is put only against the upper weathered soil zone (Fig. 4.13). Bore wells have proved their merit as drinking water wells when the discharge requirement is limited. Bore wells for irrigation purpose are also coming into vogue, especially with drip irrigation systems.

In case of wells with very low discharge, there is considerable loss of water in conveyance and application. In such cases, a storage tank is constructed to store water, from which the desired rates of flow could be allowed into the water conveyance system. A lined conveyance system is desirable. The other disadvantages of such wells is the excessive drawdown, resulting in high head and leading to high suction heads. Therefore, generally, submersible and jet pumps have to be used.

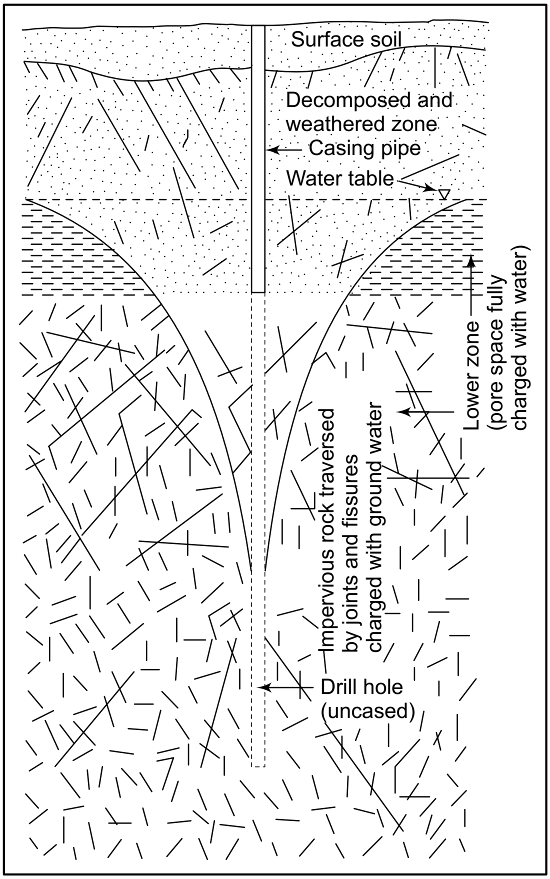


Fig. 4.13 Schematic sketch illustrating a bore well tapping the fissured zone in a hard rock area. Note the soil cover overlying the hard rock

Skimming Wells

The Indo-Gangetic plain is mostly underlain by a huge water-bearing aquifer, formed by alluvial deposits which at some places contain native saline water of the sea. The deep ground water is highly brackish (Zuberi and McWhorter, 1973). In the upper portion, however, fresh water has accumulated through seepage and deep percolation from rainfall, rivers, canals and cultivated fields. This upper layer of fresh water is thick near the source of recharge (rivers, canals, etc.). This layer of water is of good quality and can be used for irrigation.

When a well in such an aquifer is pumped, the reduced head towards the well causes an upconing or mounding of the fresh water and salt water interface under the well and eventually the well begins to draw low-lying saline water, unless special care is taken in the design of the well and the rate of pumping. Wells that are used for obtaining only fresh water in such situations are called *skimming wells*, as they are used to skim the fresh water from above the saline water with a minimum mixing, either within the well or within the aquifer.

4.1.5 Multiple-Well System

A multiple-well system is a group of closely installed shallow tube wells, usually connected to a common header pipe or manifold and pumped by suction lift of a centrifugal pump (Fig. 4.14). Such a system is also known as a well-point system or battery of wells. The individual wells in a well battery may be strainer wells or cavity wells, depending upon the characteristic of the water-bearing formation. A battery of wells is specially adapted under the following conditions:

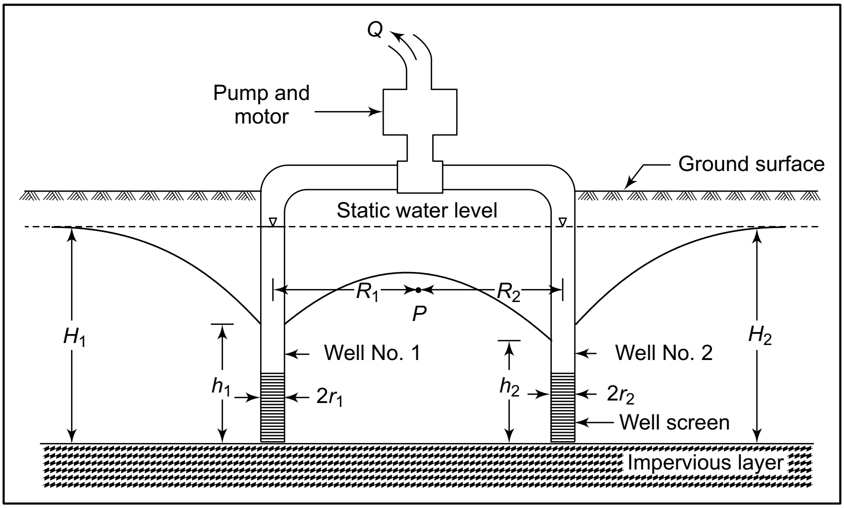


Fig. 4.14 Vertical section of two wells in an unconfined aquifer in a battery

(i) Where the water table is at shallow depth.
(ii) Where the installation of medium and deep tube wells is not economical.
(iii) Where the hydraulic characteristics of the aquifer are poor.
(iv) Where the thickness of the aquifer is limited.
(v) Where salts are present in the deeper layers of the water-bearing formation.
(vi) Wherever there is a problem of waterlogging.
(vii) Where the conditions are such that a constant level of water is required to be maintained at some depth from ground surface.

As more wells are introduced into a given area, the discharge of each existing well may decrease with time, although the total discharge from the aquifer may increase. When two or more wells are installed in a manner such that one falls in the area of influence of the other, an overlapping of the cones of depression is experienced (Fig. 4.14), which results in an increased drawdown in each well. Consequently, there is a decrease in discharge of individual wells. Thus, the relationship between discharge and time may not be unique for a well, but may depend on the operation of the well itself as well as of neighbouring wells. The farther apart the wells are spaced, the lesser their mutual interference but greater the cost of connecting pipelines. Studies on the hydraulics of multiple-well systems have revealed that there is no particular advantage in spacing the wells farther than 16 to 24 m apart. The practice, therefore, is to install wells such that each well is outside the predominant area of influence of the other.

In a multiple-well system, the wells may be arranged in various geometric patterns, either as isolated groups or as a continuous pattern extending over a large area. Generally, two wells in a straight line, three wells in a triangular pattern, and four wells in a square pattern are used. In India, battery operation of shallow tube wells has been adopted in some deltaic areas.

4.1.6 Radial Wells and Infiltration Galleries

Ground water collection through horizontally laid perforated pipes and galleries is an age-old concept. It is mainly used in water supply projects, to tap shallow ground water from river beds or areas close to streams or surface water reservoirs.

Towns and villages in rural areas of developing countries are often built along rivers or streams or beside lakes. When the stream beds or lake shores are sandy, it is often possible to locate gravel beds, which are excellent sources of naturally filtered ground water for domestic water supply. Many of the early public water supplies in the USA and other developed countries relied on shallow infiltration galleries for their supply.

The potential source of water in shallow infiltration galleries is seepage from streams or other surface water bodies. The shallow depths of traditional infiltration galleries results in low water yields. As a consequence of limited depth, infiltration galleries are also prone to contamination, unless protective measures are undertaken. However, infiltration galleries continue to be a potential water source for domestic water supply in developing countries.

Radial Collector Wells

A radial collector well system comprises a series of horizontal wells discharging water into a central caisson (Fig. 4.15). Like infiltration galleries, they are located at or close to rivers and other surface

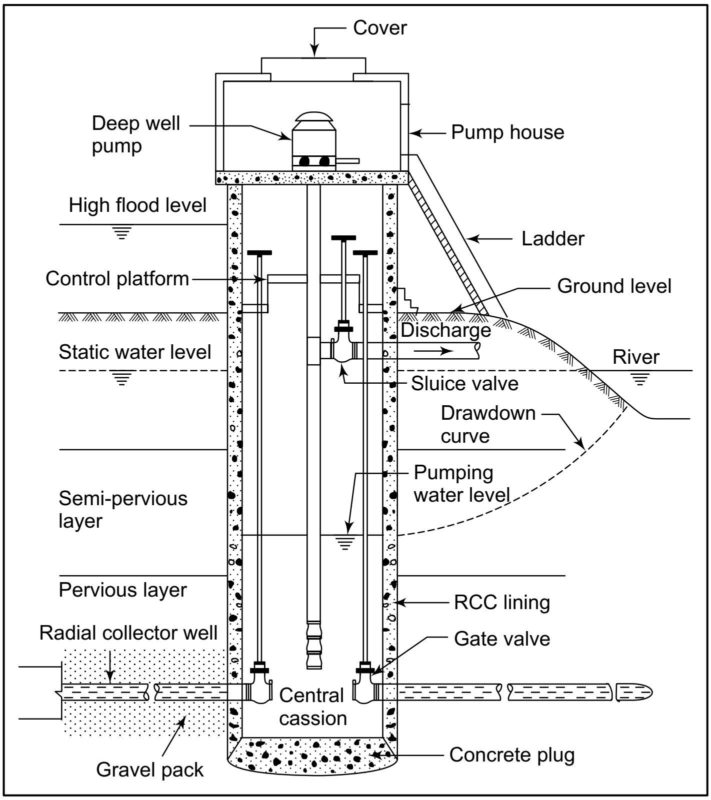


Fig. 4.15 Radial wells feeding a sump fitted with a vertical turbine pump

water bodies. A typical caisson is about 4 m in diameter and 25 to 40 m deep. It may be extended up to the shallow bed rock or clay layer. It is made of reinforced cement concrete sections, brick or stone masonry. The bottom of the caisson shoe is sealed with a concrete plug. Port holes, to accomodate radial wells, are provided about 1 m above the bottom of the caisson.

From near the bottom of the caisson, horizontal well screens are projected radially. The diameters of the horizontal screens vary from 15-60 cm, depending on their estimated yield and design velocities. Each pipe is provided with a well point. The well screen assembly is pushed into the aquifer with the help of hydraulic jacks aided by an air compressor and descending under hydrostatic pressure.

The open ends of the horizontal screen pipes project inside the caisson and are fitted with sluice valves and vertical back-wash pipes which extend to ground level and can be operated from there. The radial wells are back-washed and properly developed. Water enters from the surrounding aquifer, flows under gravity into the central caisson, and is pumped. Entrance velocities in radial wells are often of the order of 30 cm/min, after allowing for blockage by the gravel envelope around it. Vertical turbine pumps or submersible pumps with control switches located away from the pump are provided to pump water from the collector well.

Infiltration Galleries

Infiltration galleries may be described as trenches dug in river beds, either parallel to the axis of the river or transverse to it, in which are laid perforated pipes (Fig. 4.16) or masonry-lined galleries with openings to permit the entry of water (Fig. 4.17). Infiltration galleries are preferred to surface water pumping in rural water supply schemes, as it does not require the usual filtration plant and the accompanying heavy expenditure.

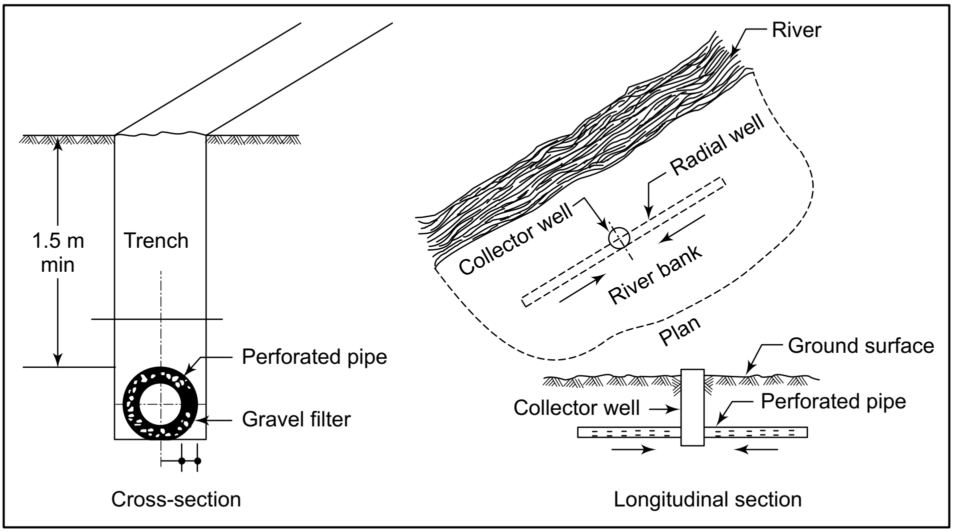


Fig. 4.16 Views of infiltration gallery lined with perforated pipe

A graded gravel filter surrounds the perforated pipe which is laid on a prepared filter bed. After laying, more filter material is added to completely surround the pipe. The size of gravel varies from 12-25 mm. The thickness of the filter varies from 30-40 cm. In case of masonry-lined galleries, the gravel envelope is laid on either side of the vertical walls. The filter prevents the blocking of pipes/galleries by the on-rush of fine sand from the river bed. In some installations, corrugated galvanized iron pipes, perforated at close intervals and back-filled with gravel or crushed rock, are used.

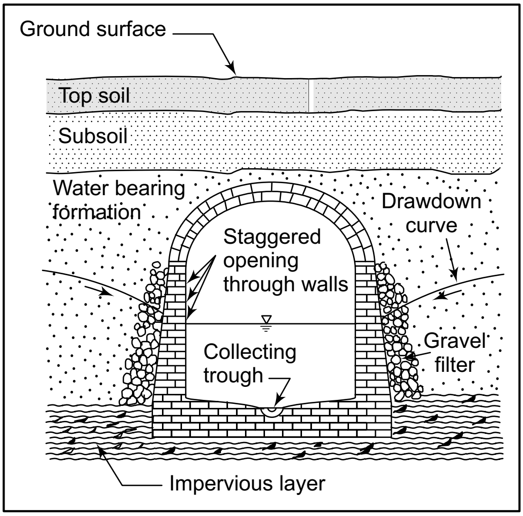


Fig. 4.17 Sectional view of brick-masonry lined infiltration gallery

The length of the pipe or gallery is determined by the quantity of water available and the time required to pick up the desired quantity. The pipes/galleries converge into a collector well, as in the case of radial wells. The collector well is made of reinforced concrete rings, brick or stone masonry, or porous concrete.

The difference in water level in the stream and the collector well is the drawdown. With increase in the rate of pumping, the drawdown increases correspondingly till a critical point is reached, when fine sand rushes to the filters and starts choking the pipe/gallery. The peak rate that can be attained without chocking is called the yield of the gallery, which decreases with increase in depth of the sand layer. However, it should be below the static water level during the dry season, and not so shallow as to be influenced by scouring during floods. The bottom of the gallery/pipe should be at least 1.5 m below the lowest summer water level. The yield from infiltration galleries may range from 15 to 30 litres per minute per metre length of the gallery.

In projects to tap water from hillside springs, through infiltration galleries, provision for a check dam or subsoil barrage downstream of the gallery system, is often made to raise the ground water level and increase the yield of the gallery. The dam should be keyed to the river bed or an impermeable layer, and extended to the bank.

Sanitary Protection of Infiltration Galleries

The general principles in the sanitary protection of wells discussed in Sec. 4.5, apply to infiltration galleries as well. The galleries should be located away from all possible sources of pollution. Diversion ditches should be built around them in order to prevent surface water from running directly over them and entering without adequate natural filtration.

4.2 SELECTION OF THE TYPE OF TUBE WELL

The type of tube well to be adopted for a particular use depends on various conditions, such as location of the water-bearing formation, size of the land holding, quality of water in different formations, and the depth of the water table. Deep tube wells in many countries are generally government owned and are used either for irrigation or drinking water supply, as community projects. The following criteria may be used for the selection of the type of tube well for an intended use:

(i) Ground water characteristics of a region should be clearly demarcated, showing the location of water-bearing formations and their properties, quality of water and the possible yield of wells. Deep tube wells for irrigation may be constructed only in areas where the water table is deep, high yielding aquifers are available at deeper depths and for community wells constructed by the government or farmers cooperatives. However, if the quality of ground water is not fit for irrigation at greater depths, it will be necessary to limit the well to a shallow depth.

(ii) The first step in constructing private tube wells should be to explore whether successful cavity wells can be constructed. If feasible, cavity wells would provide low-cost wells.

(iii) If cavity tube wells are not feasible but the aquifers are located at shallow depths, the first attempt should be to have coir or bamboo strainer wells, because of their low cost.

(iv) If coir/bamboo strainer wells are not feasible due to deeper depths or unfavourable underground strata, alternatives like agricultural strainer or PVC strainer tube wells may be explored.

(v) Gravel-pack slotted-pipe tube wells are economical and suitable for aquifers located at deeper depths. They are also suitable in shallow tube wells when the aquifer comprises of a mixture of fine and coarse formations.

(vi) In areas with limited aquifer thickness at shallow depths, or poor quality ground water underlain with good quality water in the upper layer, a multiple-well system may be adopted for irrigation wells.

(vii) Driven and jetted tube wells have low yields and their construction is limited to shallow depths in soft unconsolidated formations which are free from boulders and other obstructions. They are commonly used for domestic water supply.

(viii) Infiltration galleries are desirable to pump water from sandy river beds for drinking water supply.

4.3 PLASTIC PIPES FOR TUBE WELL CASINGS AND STRAINERS

Plastics are popular for tube well casings and strainers, especially in regions with problems of salinity in ground water. The conventional mild steel pipes used in tube wells are prone to corrosion and incrustation under poor quality ground water. Alternative metals are brass and stainless steel, both of which are prohibitive in cost under the economic conditions prevailing in many developing countries.

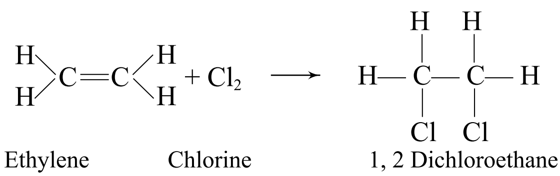
Plastic pipes, being non-metallic, are resistant to corrosion. They have comparatively low coefficients of friction and hence, better hydraulic performance. They are lighter in weight than metal pipes of equivalent specifications, the weight being only about 1/4-1/3 that of mild steel pipes of identical dimensions. Hence, they offer considerable advantages in transportation and installation. Their durability is about twice that of mild steel pipes in good quality ground water, while it is several times longer in saline aquifers.

High density polyethylene (HDPE) pipes, fibre glass reinforced plastic (FRP) pipes and rigid polyvinyl chloride (PVC) pipes are possible alternatives in the use of plastics in tube wells. FRP pipes offer all the advantages of plastics. However, vertical slots are difficult to be cut in them as it is likely to weaken the reinforcement. The equipment required for its fabrication is comparatively expensive, as it is to have components to provide for the control of the glass content and the pattern of windings of the rovings. They are more expensive than HDPE and PVC pipes. FRP pipes, however, are potentially feasible for tube wells, due to their adaptability for deep wells.

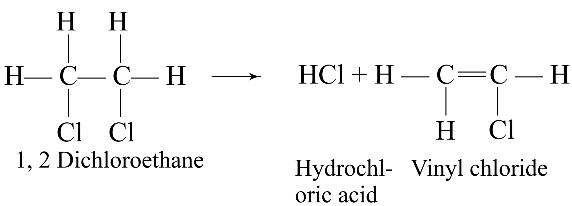
HDPE pipes are safe for use in water conveyance, in domestic water supply and irrigation. However, they have limited use in tube well screens since in a slotted pipe, the fibres tend to protrude which can attract incrustation and increase the flow resistance and reduce the yield. They require large wall thickness due to their flexibility and lower strength. The slots cannot be close to each other because the fibre rib between the slots tends to get distorted on loading. Rigid PVC pipes are by far the most commonly used plastic pipes in tube wells. However, their use, with the technology available at present, is limited to shallow (< 80 m) and medium deep (< 200 m) tube wells. Their low tensile strength and difficulty in obtaining joints of adequate strength make them difficult for adoption in deep tube wells. They also require special care in installation to ensure proper verticality for the well.

4.3.1 Rigid PVC Pipes for Tube Wells

Rigid PVC pipes are suitable for tube well casings and screens under aquifer conditions prone to corrosion and incrustation. It is a polymer of vinyl chloride. It is prepared from ethylene, a constituent of the gas mixture formed in petroleum cracking. Ethylene is made to react with chlorine to form dichloroethane:



When heated dichloroethane splits into hydrochloric acid and vinyl chloride:



The vinyl chloride is then polymerized, i.e. the molecules are combined to form long chains of polyvinyl chloride.

4.3.2 PVC Casing Pipes

Rigid PVC well casings should be capable of resisting the collapse pressure of the external loads to which they are subjected during and after installation. The well pipe assembly is most vulnerable during installation.

PVC resists most acids, alkalies and solutions of other chemicals, and can handle water with *p*H values ranging from 2 to 12. They do not rust or corrode on exposure to moist, humid or salt environments. They also have high fire resistance. However, large diameter PVC pipes are relatively more expensive than mild steel pipes.

The following are the typical physical properties of PVC pipes:

1. Specific gravity ≈ 1.4
2. Tensile strength > 550 kg/cm^2
3. Compressive strength ≈ 700 kg/cm^2
4. Coefficient of linear expansion ≈ 70×10^{-6} cm/°C

Compared to mild steel, the resistance of PVC pipes to hydrostatic pressure is substantially lower. While selecting PVC pipes for tube wells, it should be ensured that they are of sufficient thickness to withstand internal stresses.

The tensile load (vertical force) acts on well pipes when they are suspended in the bore hole. During the process of gravel packing, both tensile and external pressure loads act on pipes. While in operation, there are reductions in buoyant forces due to reduction in water levels. The horizontal forces acting on well pipes are due to the gravel pack and earth pressure. When the gravel packs settle, the annular space between the casing and bore hole is packed with a gravel envelope which exerts force on the pipe. Different earth zones along the well bore also exert horizontal forces on well pipes. The internal resistance of pipes are usually designed by their critical collapse pressure.

Standard Dimension Ratio (SDR)

This is the ratio between the diameter of the pipe and its thickness. By properly selecting the right value of SDR, it is possible to obtain a suitable casing of adequate thickness. The values of SDR usually range between 16 and 28 for casings and screens of shallow and medium-deep tube wells. The critical collapse resistance pressure for different values of SDR are given below:

Standard dimension ratio	Critical collapse pressure		
	Bars	metres of water	kg/cm^2
16	15	153.4	15.34
20	8 to 9	82 to 92	8.2 to 9.2
28	3 to 5	31 to 51	3.1 to 5.1

Table 4.1 presents the wall thicknesses of PVC pipes of various sizes, for shallow and medium-deep tube wells.

TABLE 4.1 Thickness of PVC Pipes for Shallow and Medium-Deep Tube Wells

Nominal size, mm	Outer diameter, mm Min.	Outer diameter, mm Max.	Well thickness, mm Shallow wells (depth upto 80 m) Min.	Shallow wells Max.	Medium wells (depth greater than 80 m but less than 250 m) Min.	Medium wells Max.
40	48.0	48.2	3.5	4.0	3.5	4.0
50	60.0	60.2	4.0	4.6	4.0	4.6
100	113.0	113.3	5.0	5.7	5.0	5.7
150	165.0	165.4	5.7	6.5	7.5	8.5
200	225.0	225.5	7.6	8.8	10.0	11.2
250	250.0	250.8	8.5	9.8	12.5	14.0
300	315.0	316.0	10.7	12.4	15.8	17.6

Source: Wavin (India) Ltd., Madras

The collapse strength of PVC tube well screens is usually in the range of 50 to 70 per cent that of casing pipes of identical size. However, because of their perforations, screens equalise pressures on the outside and inside. Hence, the screen sections of tube wells seldom fail due to collapse pressure.

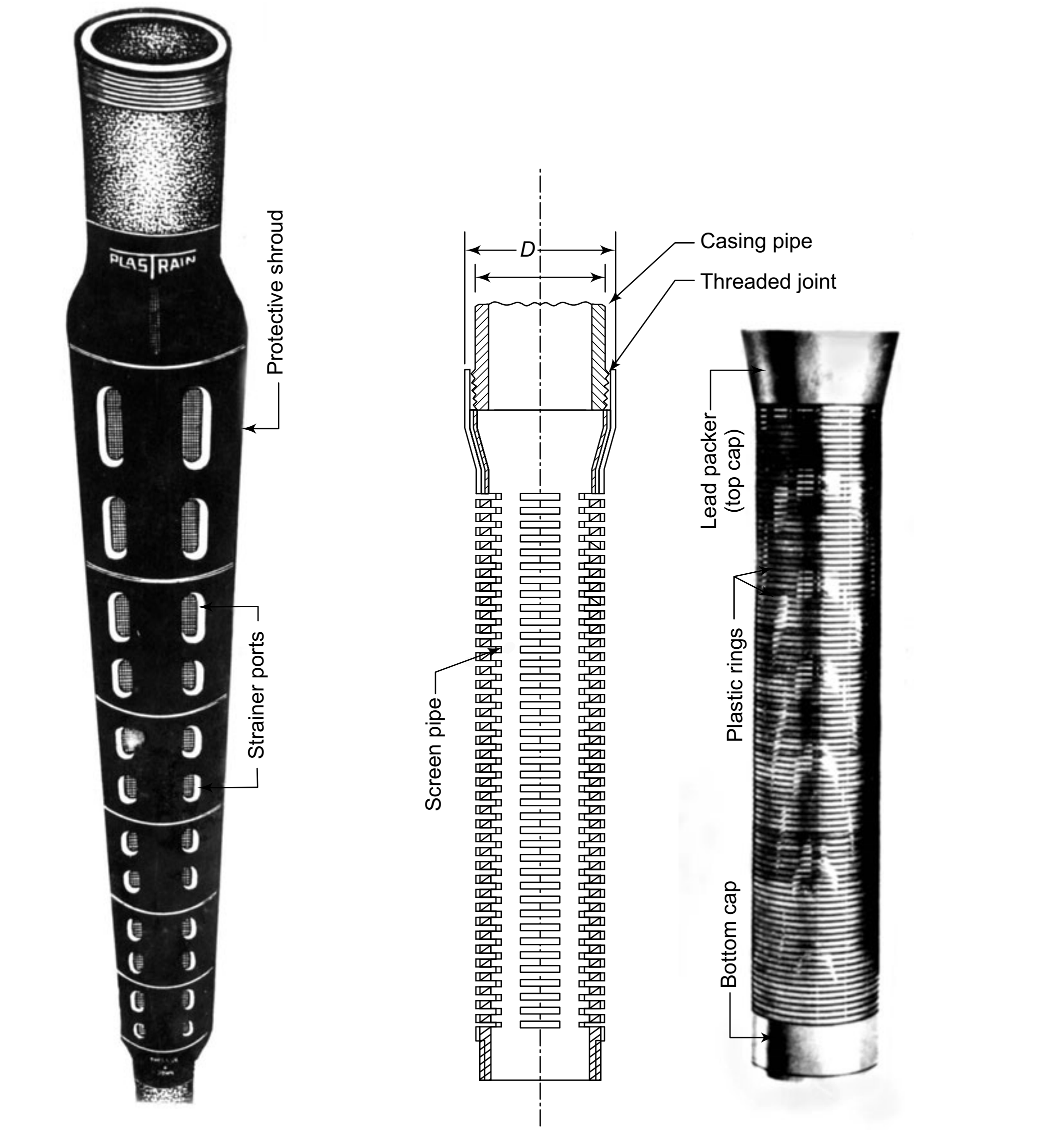
4.3.3 PVC Well Screens

Plastic/PVC well screens may vary from ordinary PVC slotted pipes to sophisticated commercial designs. Figure 4.18 presents three different types of commercially available screens. The general principles of size, shape, orientation and percentage open area of screens, described earlier, apply to plastic pipes as well.

4.3.4 Pipe Joints

Jointing of PVC well pipes may be made through spigot and socket joints, with solvent cementing or threaded joints, or by PVC metal flanges. In solvent-cement jointed spigot and socket joints, the pipe ends are cleaned, dried, and the mating surfaces roughened with emery paper. A thick coat of solvent cement is applied on the spigot and a thin layer along the inner face of the socket. The first coat is usually allowed to dry and a second one applied. The pipe ends are pushed into the socket. The joint should not be disturbed for about 5 min. Full working strength is not developed until about 24 h, and the pipe should not be subjected to loads till then. Due to the low strength of joints, solvent-cement jointing is used only in shallow wells and pipelines.

Threaded joints on spigot and socket ends provide better strength and are recommended for tube wells. Table 4.2 presents the permissible strength of joints for PVC tube wells.



(a) Filter point strainer (adapted mainly to domestic water supply systems)
Courtesy:
Plastrain, Kolkata

(b) Sectional view of PVC ribbed screen
Adapted from:
Wavin (India) Ltd. Chennai

(c) Ring type plastic well screen
Courtesy:
Evans Deakin and Co., Sutherland, Australia

Fig. 4.18 Commercial plastic/PVC strainers

TABLE 4.2 Strength of Joints of PVC Well Pipes

Nominal diameter mm	Permissible tensile strength of joints, kg	
	Shallow wells < 80 m	Medium wells 80-200 m
40	1,400	1,400
50	1,800	1,800
100	2,000	4,000
150	2,300	6,600
200	2,300	8,000

Source: Wavin (India) Ltd., Chennai.

Flanged joints are sometimes provided, even though they are not very suitable for gravel pack wells. Standard metal flanges or flanges made from PVC sheets can be used. While using metal flanges, PVC collars are welded to the pipe ends. PVC flanges themselves are welded to the pipe ends. A rubber or PVC gasket is used while tightening the flanges with bolts to prevent leakage.

Special mechanical joints are sometimes provided in PVC well pipes. The joint shown in Fig. 4.19 consists of a socket at one end of the pipe and a spigot at the other, both grooved to house a glass fibre split ring. When expanded with the aid of a wedge or a pair of long-nosed pliers, the spigotted end of the adjacent pipe can be inserted. The wedge is removed through the slot in the wall of the socket and the split ring is seated partly in the spigot groove and partly in the socket groove. A flexible plastic strip is fed around the ring to locate correctly the glass fibre ring. A small stainless steel clip can be pressed into the two holes in the split ring to prevent it from rotating and to facilitate disassembling of the joint, if necessary.

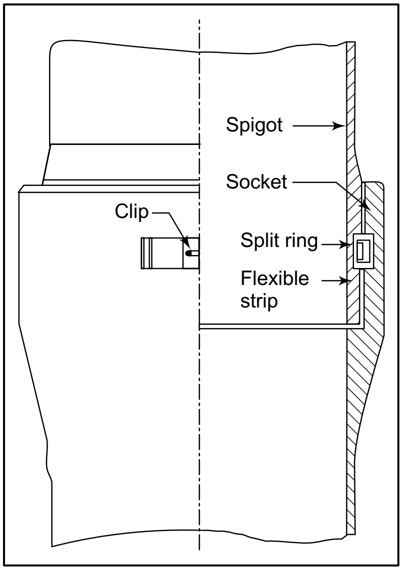


Fig. 4.19 Mechanical locking joint (half-sectional view) for rigid PVC well pipes.
Adapted from: Bristol Aeroplane Plastics Ltd., Bristol, England

4.3.5 Special Precautions in the Installation of PVC Pipes

General procedures of well pipe installation described in Chapter 5 apply to PVC pipes as well. PVC pipes are usually supplied in lengths of 6 m or less. The pipe is hung by means of an iron rope or iron band put on the shoulder of the pipe to which is fixed a suitable clamp. The pipe is centred and allowed to descend into the well. To avoid slipping and dropping of a lowered pipe, the sleeve end of the female pipe must always be in an upward position so that the upper (male) pipe can be inserted and jointed.

For ease of installation, soft soap may be applied on threads. Centering guides (Fig. 4.20) should be fixed at regular intervals to ensure verticality. Care must be taken to ensure that the gravel is uniformly distributed around the pipe and no lodging occurs in the bore hole. The gravel must be fed slowly and not dumped at a high rate. Development of PVC wells is normally done by the *back-wash* method.

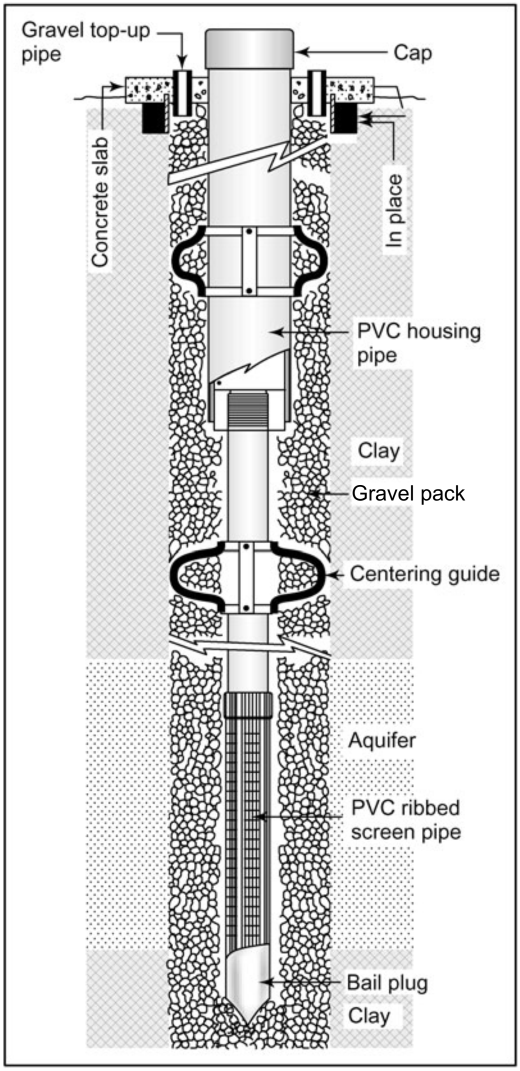


Fig. 4.20 Schematic sketch illustrating the installation of PVC plain pipes for housing and PVC ribbed pipe for well screen
Adapted from: Wavin (India) Ltd., Chennai

4.4 DESIGN OF TUBE WELLS

Design of a tube well involves selecting the appropriate dimensions of the various components and choosing the proper material to be used in its construction. A good design should aim at efficient utilization of the aquifer, long useful life, low initial cost and low maintenance and operation costs.

The design guidelines presented in this chapter are primarily for screen-type deep wells in unconsolidated material. However, the basic principles apply to all types of wells. The tube well structure consists of two main elements, i.e. casing and intake. The casing portion consists of a housing for the pumping equipment and a vertical conduit (plain pipe) through which water flows upward from the aquifer to the level where it enters the pump.

Water enters the well from the aquifer through the intake which is usually the well screen. Hence, the design of the intake structure requires careful consideration. In a consolidated rock aquifer, the intake portion of the well is usually an open bore hole drilled past the water-bearing layer to an adequate depth. Similarly, in case of a cavity well in which only the casing is used, the intake portion consists of the cavity of the well.

The design of a tube well involves the following steps:

1. Mechanical analysis of samples of the underground formation obtained from various depths and the preparation of a well log
2. Design of housing pipe and well casing (plain pipe)

3. Design of well screen
4. Design of gravel pack
5. Design for sanitary protection

4.4.1 Analysis of Particle Size Distribution of the Aquifer

The determination of the particle size distribution of aquifer materials collected from various depths is of prime importance in the design of the intake portion of a tube well. Dry sieve analysis of the formation samples obtained during the drilling of test holes or production wells reveals the characteristics of the water-bearing formations. The results provide the basis for decisions about the specifications of the well screens and the design of the gravel pack.

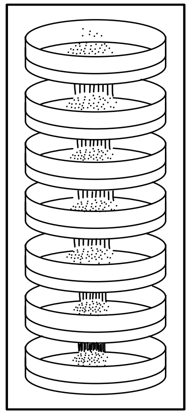


Fig. 4.21 Set of sieves for analysing aquifer samples

The standard procedure for analysing sand/soil samples by the dry-sieving method is adopted. A set of sieves (Fig. 4.21) conforming to Indian Standard, IS: 460-1985, or the standard adopted by a particular country, is used. The weight of the material retained on each sieve is recorded. These weights are then expressed as a percentage of the total weight of the sample and a graph plotted through the cumulative per cent of the sample retained on a given sieve and all the other seives above it, versus the size of the given sieve, expressed in mm (Fig. 4.22). The percentage of the sample retained is plotted on the *y*-axis and the size of the sieve-opening or 'particle size' on the *x*-axis. It is common practice to plot the graph on semi-log paper, with the *x*-axis on the logarithmic scale. The size of the sieve opening is considered to be the diameter of the smallest particle retained by each sieve. Figure 4.22 represents the typical sieve analysis curves for distinct classes of aquifer materials, indicating the water bearing characteristics of the formation and the need for artificial gravel pack. The following terms are used for defining the size characteristics of aquifer materials.

Effective Size 'd_{10}'

The term 'effective size' is defined as formation particle size, where 10 per cent of the sand is finer and 90 per cent coarser. For example, the class C curve of Fig. 4.22 shows that 90 per cent of the sample consists of sand grains larger than 0.25 mm, or that 10 per cent is smaller than this size. Thus, the effective size of the formation material is 0.25 mm.

Uniformity Coefficient, C_u

This is a ratio expressing the variation in grain size of a granular material. It is usually measured by the sieve aperture that passes 60 per cent of the material, divided by the sieve aperture that passes 10 per cent of the material.

$$C_u = \frac{d_{60}}{d_{10}} \frac{(40\% \text{ retained})}{(90\% \text{ retained})}$$

Thus, in Class C curve (Fig. 4.22), the uniformity coefficient is 0.75 mm divided by 0.25 mm, i.e. 3. This ratio was proposed by Hazen (1893) as a quantitative expression of the degree of assortment of water bearing sand, as an indicator of porosity. The value of the coefficient for complete assortment (one grain size) is unity, while for fairly even-grained sand it ranges between 2 and 3. For heterogeneous sand, the value will be high. Generally, a material is classified as uniform if the uniformity coefficient C_u is less than 2.

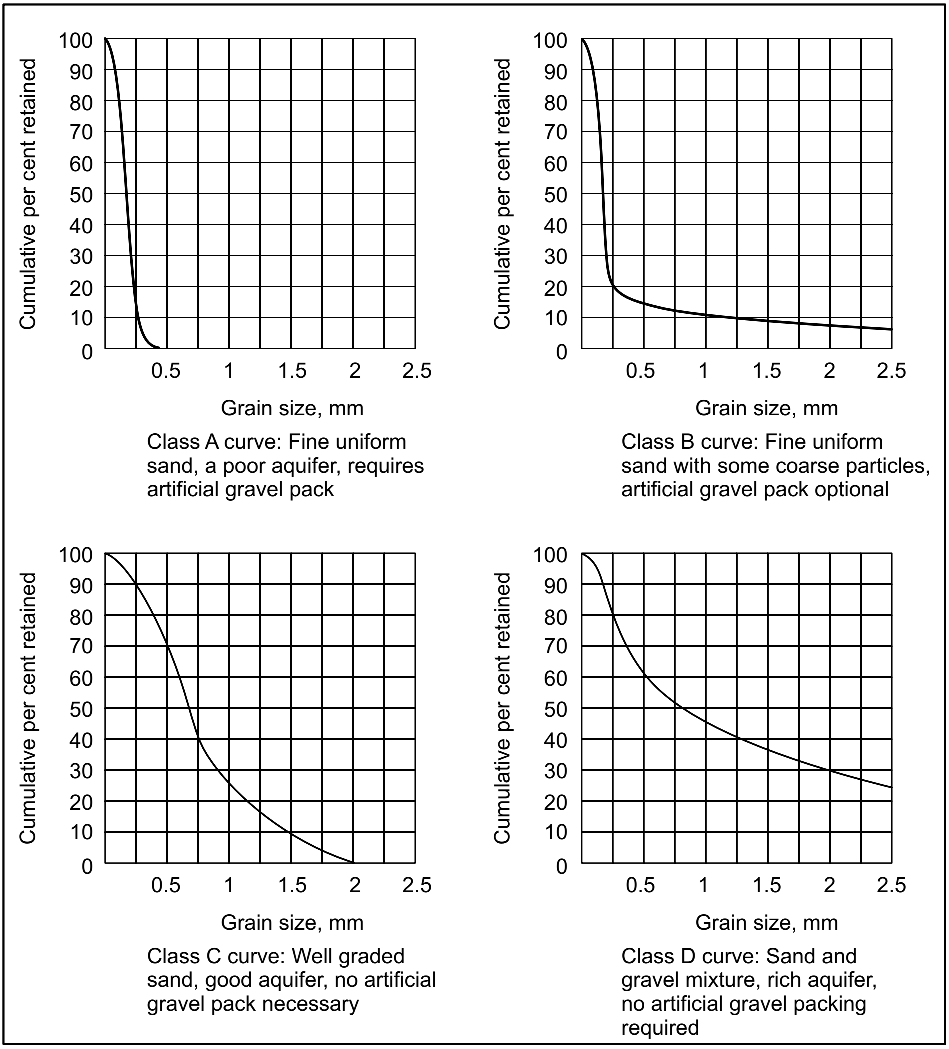


Fig. 4.22 Typical sieve analysis curves of water bearing sands and gravels

4.4.2 Design of Housing Pipe and Well Casing

The design of the housing pipe and well casing will include the selection of a suitable material and diameter and thickness of pipe.

Diameter of Housing Pipe

The housing pipe is an enlarged section of the well casing at the top of the well, in order to house a deep-well turbine pump or submersible pump. It should be large enough to accommodate the pump with adequate clearance. The annular space between the pump and the inner diameter of the housing pipe also permits the installation of an air line to measure the depth to pumping water level. The housing pipe should be at least 5 cm more in diameter than the nominal diameter of the pump. The diameter and thickness of the housing pipe (steel pipe), as recommended by U.S.B.R. (Ahrens, 1970), are given in Table 4.3.

TABLE 4.3 Diameter and Thickness of Housing Pipes of Tube Wells for Different Sizes of Turbine/Submersible Pumps

Discharge 1/min	Nominal diameter of pump, cm	Diameter of housing pipe cm	Thickness of housing pipe mm
475	12.5	15.0–20.0	1.5–3.5
1150	15.0	20.0–25.0	1.5–3.5
2275	20.0	25.0–30.0	2.0–3.5
4550	30.0	35.0	2.0–5.0
7500	35.0	40.0	2.0–6.0
11500	40.0	45.0	2.0–6.0

Source: Ahrens (1970)

Depth of Housing Pipe

The depth of housing pipe below the ground level is selected such that the pump is always submerged in water. Since the pump is lowered in the housing pipe, it must be set a few metres below the lowest drawdown level, taking into account the seasonal fluctuations in the spring level or water table, interference from adjoining tube wells and the likely lowering of the water table due to future development of ground water in the area.

Diameter of Well Casing Pipe

The diameter of the pipe of the well section below the pump housing is fixed by the permissible velocity of water through the pipe. Since the strata suitable for strainers are usually met in layers at different levels, the velocity of water in a pipe of a given size would not be constant, but will increase towards the top. The velocity may vary between limits of 1.5-4.5 m/s. It is theoretically possible to reduce the size of a pipe from the top to the bottom such that the velocity is more or less constant throughout the pipe length. However, it is not an economical proposition. The usual practice is to provide a pipe of constant diameter. A velocity of the order of 2.5-3 m/s is found to be most suitable. Having fixed the velocity, the diameter of the pipe can be determined for a given discharge. The relationships $Q/v = a$ and $a = \pi d^2/4$, where Q is the discharge, a the area of cross-section of pipe, and d its diameter, are used to determine the pipe size.

Thickness of Well Casing Pipe

The casing pipe must resist substantial stress from compressive, tensile and shear forces. In addition, it should last for 20-40 years after installation. Steel has proved to be one of the most practical materials. Steel pipes are produced in several thicknesses. Heavier pipes should be used where severe corrosion is expected. If the soil and water are only mildly corrosive, lighter wall thicknesses may be adequate. The thickness of well casing pipe is usually recommended as a function of the diameter and depth of the well. The thickness of the well casing, usually adopted under normal conditions (Ahrens, 1970), is given in Table 4.4. The values of the thicknesses given apply to plain as well as perforated casings (well screens).

TABLE 4.4 Suggested Thickness of Well Casing Pipe, mm

Depth of well	Diameter of well casing, cm				
m	15	20	25	30	35
0 – 10	1.59	1.59	1.59	1.98	1.98
10 – 20	1.59	1.59	1.59	1.98	1.98
20 – 30	1.59	1.59	1.59	1.98	1.98
30 – 40	1.59	1.59	1.59	1.98	1.98
40 – 50	1.59	1.59	1.98	1.98	2.78
50 – 60	1.59	1.98	1.98	2.78	2.78
60 – 70	1.98	1.98	1.98	2.78	2.78
70 – 80	1.98	1.98	1.98	2.78	3.57
80 – 90	1.98	1.98	2.78	2.78	3.57
90 – 100	1.98	2.78	2.78	3.57	3.57
100 – 110	1.98	2.78	3.57	3.57	3.57
110 – 120	1.98	2.78	3.57	3.57	4.76
Above 120	2.78	3.57	3.57	4.76	4.76

Source: Ahrens (1970)

4.4.3 Bore Size and Well Depth

The bore diameter and depth of wells are important parameters influencing the yield of wells. The size of the well bore should suit the diameter of the well casing. Gravel pack wells require extra bore size to accommodate the gravel pack in the annular space between the bore hole and the well casing. The depth and thickness of the water-bearing formations influence the depth of the well. Shallow tube wells usually tap water only from the top unconfined aquifer, while deep tube wells draw their supplies mainly from the confined aquifers below the unconfined aquifer.

Bore Size

The bore of a tube well has to be at least 5 cm bigger in diameter than the casing pipe. This will facilitate the lowering of the pipe. Thus, for a tube well of size 20 cm, a minimum bore of 25 cm is necessary. If gravel pack is to be used, the minimum diameter should be twice the thickness of the gravel pack plus the outside diameter of the casing pipe. However, in case of tube wells drilled with reverse rotary rigs, the diameter of the bore is about 60 cm. In such a situation, if the tube well diameter at the screen section is 15 cm, the thickness of the gravel pack will be 22.5 cm up to the housing. If the housing is of 30 cm diameter, the thickness of the gravel pack will be reduced to 15 cm. In case of a well drilled with a direct rotary-drilling rig, different diameters of the bore could be obtained by under-reaming, with a view to use lesser thicknesses of the gravel pack. However, the thickness of the gravel pack should not ordinarily be less than 7.5 cm.

Well Depth

The depth of a tube well depends upon the locations of water-bearing formations, desired yield of the well and economic considerations. Generally, a well log showing the locations of water-bearing formations is prepared and the strata to be tapped selected (Sec. 4.4.4). The depth of the well is decided on the basis of the hydraulic conductivity of the aquifer material and the desired yield of the well. Often, if the desired yield is not possible at a reasonable depth, it will be necessary to limit the depth without achieving the desired discharge. Sometimes the depth of the well will have to be curtailed if poor quality ground water is encountered in lower aquifers.

4.4.4 Selection of Strata to be Screened

After the particle size distribution of the formation samples are obtained from various depths, the average size, effective size and uniformity coefficient of the aquifer material are marked on the strata chart. This would help to determine the thickness and relative permeability of each aquifer. The permeability of the aquifer is proportional to the square of the effective grain size d_{10}, for the same uniformity coefficient, C_u. In case two samples have the same effective size, the sample with a lower value of uniformity coefficient is more permeable.

In case of an unconfined aquifer which is too thick and homogeneous, it is desirable to provide the screen in the lower 1/3rd thickness. In case of confined aquifers with thick and nearly homogeneous strata, about 80-90 per cent of the central part of the aquifer should be screened. Where the aquifers are too thick and heterogeneous, it is common practice to place screens opposite the more permeable beds, leaving about 30 cm depth both at the top and bottom of the aquifer, so that the finer material in the transition zone does not move into the well. The top of the screen should be set below the lowest pumping level allowed, keeping in view possible fluctuations of the water table.

4.4.5 Design of Well Screen

The well screen is the most important component of a well. The life of a well is governed mainly by the life of the screen, which should, therefore, be carefully designed. The basic requirements of a well screen are:

(i) It should be resistant to corrosion and deterioration.
(ii) It should be strong enough to prevent collapse.
(iii) It should offer minimum resistance to the flow of water, and
(iv) It should prevent excessive movement of sand into the well.

A screen in actual practice may represent a compromise of these desirable characteristics.

The design of a well screen will include the determination of the diameter of the screen, its length, percentage of open area, size and shape of each slot, and thickness and material of the screen. The length of the screen and its placement are governed by the thickness and location of the aquifers. In case an adequate thickness of water-bearing formations is available, the length of the screen, its diameter, and per cent open area, are governed by the head loss through the screen and its effect on the losses in the aquifer, in addition to the initial cost of the screen. The size of the slot opening is governed by the size of the gravel or aquifer material which it has to retain. The design principles for different elements of well screen are discussed below:

Slot Opening

Choosing the right width of the slot of a well screen is one of the important steps in well design. Over-sized slots will pump finer materials (sand, silt and clay) indefinitely and clear water will be difficult to obtain. Under-sized slots will provide more resistance to the flow of ground water, resulting in more head loss and corrosion. Fine slots are also blocked by small sand and silt practicles which are carried upto the well screen as suspensions. The problem of clogging is reduced as the size of well screen openings are increased. Therefore, well screen slot openings should be as wide as possible. It is determined by matching the size of the opening with the grain-size distribution of the material surrounding the screen. In practice, the slot size varies from values as low as 0.2 mm to as large as 5 mm. The logical steps for the design of slot openings are as follows:

(i) *Non-Gravel-Pack Wells*

The design of the slot opening of a non-gravel-packed or naturally developed well is based on the sieve analysis data of the samples representing the water-bearing formation. A grain size distribution curve is plotted for each sample. For a homogeneous formation, the size of screen opening taken is one that will retain 40 per cent of sand if the ground water is not corrosive. However, if the ground water is corrosive, the screen slot size should be one that will retain 50 per cent of the sand.

The optimum size of the slot opening is determined by selecting a point on the particle size distribution curve of the aquifer, where the 40 per cent (or 50 per cent, as the case may be) line intersects the sample-analysis curve and then determining the screen opening from the horizontal scale.

In actual practice, non-homogeneous formations, i.e. stratified aquifers, are often encountered. In such cases, the slot size should be selected for the finest aquifer if the average size of the coarsest aquifer is less than four times the average size of the finest aquifer. Otherwise, the slot size should be selected separately for each aquifer, according to the grain size distribution curves of the different strata, using the criteria described above. However, in this case it should be ensured that if fine materials overlie the coarse material, at least 60 cm of the screen with slot size designed for the materials, is extended into the coarse stratum below. Moreover, the slot size of the screen to be installed in a coarse stratum should not be more than double the size of the overlying finer material. This procedure will take care of mistakes, if any, in determining the precise thickness of each aquifer layer. In case of limited thickness of different layers of aquifer formations, it becomes difficult to follow the above procedure strictly. Hence, screen lengths with uniform widths of slots, designed on the basis of the finest aquifer material, are often provided. As indicated in the design procedure, the selection of the slot size indicates that 60 per cent of the formation material will be pumped out during development, which will result in the removal of fine particles around the well screen. This will ensure the supply of sand-free water.

(ii) *Gravel-Pack Wells*

Size of openings of the slots of well screens for a gravel-packed well are determined on the basis of the particle size distribution curve of the gravel. On this curve, a point is located indicating the 90 per cent size of the gravel to be retained. Through this point, a line is drawn parallel to the y-axis, meeting the x-axis at another point which indicates the slot size of the well screen. The actual size of the slot is fixed at ± 8 per cent of the above size, depending on the size of the tool used in making the slots of the well screen.

Percent Open Area

Water flows more freely through a screen with large open area than through one with limited open area. When the open area of the screen is large, the entrance velocity is low and head loss at the screen is minimum. Corey (1949), observed that little or no increase in well efficiency results, when the open area is greater than 15 per cent of the total surface area of the screen. Further, an open area larger than about 15 per cent affects the structural strength of slotted pipe well screens.

Ahrens (1970) stated that little or no increase in well efficiency results from open areas greater than about 25 per cent, whereas efficiency falls rapidly as the open area becomes less than 15 per cent. When a screen is placed in an aquifer, sediment will settle down around it and partially block the slot openings. Walton (1962), observed that, on an average, about one-half of the open area of a well screen is blocked by aquifer materials. Based on these studies, it may be concluded that it is desirable to provide an open area of about 20 per cent for well screens other than slotted pipes.

Diameter of the Screen

The considerations which govern the diameter and length of the well screen are the per cent open area of the screen, characteristics of the aquifer, cost of the screen, discharge to be pumped from the well, and head loss through the aquifer and the screen. The diameter should ensure that the area of the opening available in the screen for flow of water, after giving allowance for possible clogging of the screen, should produce a screen entrance velocity of not more than 3 cm/s. However, in areas where sufficient sand thickness is not available, a maximum entrance velocity of 5 cm/s may be permitted. It should also be ensured that the percentage of slot area to screen surface area is about 20 per cent. Generally, the screen diameter is kept the same as that of the casing. Table 4.5 gives the recommendations of USBR (Ahrens, 1970) for casing and screen diameters for various discharges to be pumped from the well.

TABLE 4.5 Recommended Diameter of Casing Pipe and Well Screen

Discharge	**Casing pipe/screen diameter, cm**	
1/min	**Minimum**	**Recommended**
475	10	10
475 – 1125	15	15
1125 – 3000	20	25
3000 – 5250	25	30
5250 – 9500	30	35
9500 – 13300	35	40

Source: Ahrens (1970)

Screen Length

The optimum length of the well screen depends upon the thickness and stratification of the aquifer and the available drawdown. The following guidelines may be followed under various aquifer conditions.

(i) Water Table Aquifers

In case of homogeneous water table aquifers, the bottom one-third of the aquifer may be screened. However, in order to obtain higher specific capacity, sometimes the bottom half of the aquifer is screened.

(ii) Artesian Aquifers

In case of homogeneous aquifers, 75 – 90 per cent of the thickness of the water-bearing sand should be screened. The percentage of the aquifer to be screened increases with the increase in its thickness. For an aquifer of thickness less than 8 m, screening of 75 per cent is satisfactory. At least 30 cm of the aquifer depth at the top and bottom of the screen should be left unscreened to safeguard against an error in the placement of screen during installation. The pumping water level should never fall below the top of the aquifer. The screen is usually located at the centre of the aquifer.

In case of non-homogeneous aquifers, it is obviously best to screen the most permeable strata. When the aquifer comprises of various layers of good water bearing strata, each strata is tapped separately by dividing the screen into sections of lengths based on the thickness of the aquifer layer and interspacing with sections of blind pipes.

Minimum Length of Screen

The length of screen to be provided in a well depends on the thickness of the aquifer available, as discussed above. However, the condition of minimum length required to keep the entrance velocity through the opening less than the permissible value must be satisfied. An entrance velocity more than the permissible value, will result in excessive pumping of sand. Sometimes, to satisfy the above condition, the design discharge of the well will have to be reduced.

The values of optimum screen entrance velocities recommended by Walton (1970), on the basis of studies made for several actual case histories of well failures due to clogging of screen openings, is given in Table 4.6.

TABLE 4.6 Optimum Screen Entrance Velocities

Coefficient of permeability cm/s	0.28	0.24	0.18	0.14	0.09	0.05	0.02
Optimum screen entrance velocities, cm/s	5.5	5.0	4.5	4.0	3.0	2.0	1.5

Source: Walton (1970)

To prevent rapid clogging, the minimum length of the well screen for a non-gravel pack well is designed on the basis of the following equation (Walton, 1962):

$$h = \frac{Q_0}{A_0 V_e} \tag{4.1}$$

where, h = minimum length of the well screen, m

Q_0 = maximum expected discharge capacity of well, m^3/min

A_0 = effective open area per metre length of the well screen, m^2

V_e = entrance velocity at the screen, m/min

Equation (4.1) is also used to determine the length of the screen in a gravel-pack well. In this case, the average value of the hydraulic conductivity of the aquifer and the gravel pack is used to determine the entrance velocity of the screen.

To determine the minimum length of the well screen, the optimum entrance velocity, based on the hydraulic conductivity of the aquifer, is determined (The practice being followed in the design of tube wells in unconsolidated formations in India is to allow a permissible entrance velocity of 3 cm/s through the effective open area of the screen). From the aquifer test, the expected capacity of the well is estimated. From the information on the open area of well screen per metre, the effective open area is determined. The screen length is then estimated using Eq. (4.1). It is recommended that a screen length greater than this value should be provided wherever possible to keep the entrance velocity lower than 3 cm/s, in order to ensure a longer life of the well.

EXAMPLE 4.1 A fully penetrating tube well in a confined aquifer has a maximum discharge capacity of 3000 1/min. The aquifer is overlain and underlain by impervious layers. The thickness of the aquifer is 22 m. Design the length of the well screen, assuming the effective open area of the available strainer to be 15 per cent and the diameter of the well 20 cm.

Solution

Effective open area per metre length of the well screen is

$$A_0 = \pi d \times \frac{15}{100} = \pi \times \frac{20}{100} \times \frac{15}{100}$$

$$= 0.09425 \text{ m}^2$$

Assuming the safe entrance velocity to be 3 cm/s or 1.8 m/min, the minimum length of well screen is given by,

$$h = \frac{3}{0.0942 \times 1.8} = 17.69 \text{ m, say 18 m}$$

The aquifer thickness is 22 m. Hence, it will be safe to provide a 20 m length of screen, which is more than the essential length of 18 m and about 90 per cent of the aquifer depth. The screen may be provided in the central portion of the aquifer, leaving one metre depth of aquifer unscreened at both ends.

4.4.6 Design of Gravel Pack

The term *gravel packing* refers to the placing of gravel around the well screen. This pack is also referred to as, *artificial gravel treatment, gravel shrouding and gravel filter*. The role of the gravel pack is to support the formation while at the same time offering increased permeability to the annular area between the screen and the aquifer. Not all water bearing formations require artificial gravel packing. Generally, formation materials with an effective size (d_{10}) less than 0.25 mm and a uniformity coefficient (C_u) of 2 or less require gravel packing. An artificial gravel pack may also be used for an aquifer containing fine material, where it is desirable to use larger screen openings than are indicated by sieve analysis. This often occurs when C_u is between 2 and 3 and d_{60} less than 0.42 mm.

Ellithorpe (1970), recommends the use of artificial gravel packing under the following conditions:

1. To stabilise fine-grained, poorly-sorted sand aquifers and to avoid sand pumping.
2. To permit the use of larger slot openings and the resultant higher well efficiency in fine-grained aquifers.
3. In formations of alternating zones of coarse and fine aquifer materials, it is difficult to position screens of various slot sizes accurately. The use of an artificial gravel pack will permit the use of a single slot-size screen and eliminate the positioning problem.
4. In deep aquifers, it may be less expensive to set a small diameter, artificially gravel-packed screen in an under-reamed section of the hole than to ream the full diameter hole to its full depth.
5. In case of loosely cemented, fine-grained sandstone aquifers, when a well is finished as an open hole, some sand particles slough from the walls of the hole, resulting in a sand pumping well. Wells in such aquifers can be constructed successfully with an artificial gravel pack.

Design Criteria for Gravel Pack

The basic principle in the design of the gravel pack is that the grading of the gravel pack must be correctly chosen in relation to the particle size distribution of the water-bearing formation. Basically, it is the relationship between the grain size of the gravel pack and the grain size of the formation that determine the proper selection. The mean grain size of the pack material bears a specific relationship to the mean grain size of the formation material. This ratio of mean sizes is called the gravel-pack ratio or pack-aquifer ratio (P.A. ratio).

$$\text{P.A. ratio} = \frac{\text{50\% size of gravel pack}}{\text{50\% size of aquifer}}$$

A number of workers have proposed different criteria for the design of gravel pack in tube wells, based on the P.A. ratio, but none has been entirely satisfactory for large scale field applications. Smith (1954) reported that ratios of 4-5 were found satisfactory for the efficient design of wells with gravel pack. It was observed, that wells having pack aquifer ratios of 7-10 were inefficient because of sand pumping. Kruse (1960) recommended that the limiting P.A ratio of the uniform-type aquifer and uniform gravel pack is 9.5. Under non-uniform conditions, this limit was 13.5. Johnson (1966) recommended the values of P.A. ratios as follows:

(a) Uniform aquifers:

$$\frac{d_{30} \text{ of gravel pack}}{d_{30} \text{ of aquifer}} = 4$$

(b) Graded aquifers:

$$\frac{d_{30} \text{ of gravel pack}}{d_{30} \text{ of aquifer}} = 6$$

The Central Board of Irrigation and Power (Anon., 1967), based on a series of laboratory experiments, recommended the following criteria for P.A. ratios:

(a) Uniform aquifers ($C_u \leq 2$)

$$\frac{d_{50} \text{ of gravel pack}}{d_{50} \text{ of aquifer}} \text{ should lie between 9 and 12.5.}$$

The lower and upper d_{50} sizes of gravel are defined by these two limits. Referring to Fig. 4.23, the d_{50} size of a uniform aquifer material is indicated by point *A*. The lower and upper limits of the d_{50} size of gravel pack, as obtained by multiplying the d_{50} size of aquifer material by 9 and 12.5 respectively, are shown by points *B* and *C*. The two lines passing through points B and C are drawn parallel to the central portion of the particle size distribution curve of the aquifer material. These parallel lines, define the zone within which the particle size distribution of the gravel should lie. The particle size distribution curve of a gravel pack is drawn by joining the bottom of the lower limiting-size curve to the top of the upper limiting-size curve (Fig. 4.23).

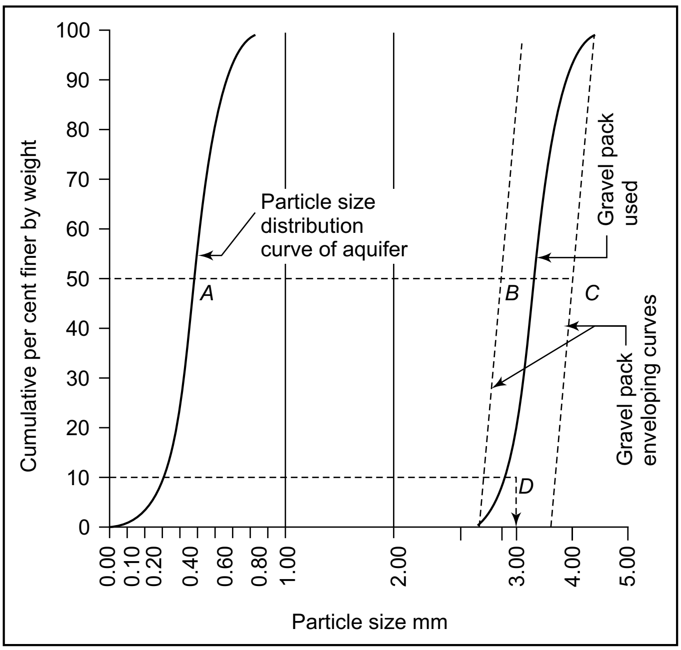


Fig. 4.23 Design of gravel pack and slot size for gravel pack tube well (Example 4.2)

(b) Graded aquifers ($C_u \geq 2$)

$$\frac{d_{50} \text{ of gravel pack}}{d_{50} \text{ of aquifer}} \text{ should lie between 12 and 15.5}$$

The lower and upper d_{50} sizes of gravel are defined by the above two limits. Referring to Fig. 4.25, the d_{50} size of a non-uniform aquifer material is indicated by point *A*. The lower and upper limits of the d_{50} size of the gravel pack, as obtained by multiplying the d_{50} size of aquifer material by 12 and 15.5. respectively, are shown by two points *B* and *C*. A line is drawn through point B, parallel to the central portion of particle-size distribution curve so that C_u of the gravel pack is ≤ 2. Another line through point *C* is drawn parallel to the line through point *B*. These parallel lines define the zone within which the particle size distribution of the gravel should lie. The particle size distribution curve of the gravel pack is drawn by joining the bottom of the lower limiting-size curve to the top of the upper limiting-size curve (Fig. 4.25)

Sometimes a gravel pack has to be provided for a well where more than one formations are to be tapped. In such case the gravel pack designed for the finest formation should be used in all the formations, provided the average grain size of the material in the coarse aquifer is less than 4 times the 50 per cent size of the material in the finest aquifer (Walton, 1970).

Example 4.2 The particle size distribution curve of an aquifer material to be tapped is shown in Fig. 4.23. Design the size of gravel pack and slot size of the well screen.

Solution

In Fig. 4.23 a plot of particle size versus cumulative percentage by weight of the formation material is given. A study of the grain size distribution curve indicates that the 50 per cent size of the formation material, i.e. d_{50} located on the curve, is 0.325 mm. The uniformity coefficient is d_{60}/d_{10} = 0.37/0.20 = 1.85.

$$\text{Since } C_u \text{ is less than 2, } \frac{d_{50} \text{ of graval pack}}{d_{50} \text{ of aquifer}}$$

should lie between 9 and 12.5. Hence, d_{50} of the gravel pack should lie between 0.325 × 9 and 0.325 × 12.5 mm or 2.925 and 4.06 mm. Lines are drawn through these two points, parallel to the central portion of the grain size distribution curve of the aquifer material. The gradation curves are shown in Fig. 4.23. The particle size distribution of gravel to be used should lie within the two enveloping curves. The minimum size of gravel is found to be 2.8 mm and the maximum size 4.7 mm. The gravel should, therefore, be screened such that the gravel size ranges between 2.8 mm and 4.7 mm.

The d_{10} size of the gravel pack is 3.00 mm. Thus, a 3-mm size slot is selected for the well screen.

Gravel Pack Material

The following are the desirable characteristics of a good gravel material:

1. It should be clean
2. The grains should be smooth and round (flat particles should be avoided)
3. It should be a hard, insoluble, siliceous material with less than 5 per cent calcareous particles (limestone). Particles of shale and gypsum are undesirable.
4. It should be uniform in size.

Screening of Gravel

The gravel used in tube wells should be clean and of the proper size. Presence of dust will give rise to problems in well development. Dirt will be washed off the gravel and drawn into the well casing during development.

Generally, the gravel size available in the market is not precisely according to design requirements. Hence, it is desirable that the gravel is properly screened to remove dust and to obtain the proper size. In India, most of the gravel is hand screened. For screening large quantities of gravel, wire screens of about 1.5 m × 1 m size are used. A set of two screens will be required for screening. Clear screen openings are provided, equivalent to the lower size of gravel material in one of the screens. The other screen is provided with clear openings equivalent to the upper size of the gravel material. The gravel pack material may be screened first through the screen with the larger openings to remove over-size particles, and then through the screen with smaller openings to screen out the under-size particles.

EXAMPLE 4.3 Design a tube well assembly to match the strata chart shown in Fig. 4.24. The grain-size distribution curve of the aquifer lying between 40 m and 85 m is given in Fig. 4.25. The anticipated drawdown is 5 m. The seasonal fluctuation of the water table is 1 m. The radius of influence and the hydraulic conductivity have been found to be 1000 m and 0.0003216 m/s, respectively.

Solution

The expected discharge of the well is given by Eq. (2.12)

$$Q = \frac{2\,\pi\,Kb\;(H - h_w)}{2.303\log_{10} R/r_w}$$

Assuming the radius of the well to be 10 cm

$$Q = \frac{2\pi \times 0.0003216 \times 45 \times 5}{2.303\log_{10}\dfrac{1000}{0.10}}$$

$$= 0.05 \text{ cumecs or } 3000 \text{ 1/min.}$$

The design calculations for various components of the tube well assembly are given below.

(*i*) *Design of Housing Pipe*

Diameter. The diameter should be large enough to accommodate the pump, with adequate clearance for installation. For a given discharge of 3000 1/min, the nominal diameter of the pump is 30 cm and the recommended diameter of housing pipe 35 cm (Table 4.3).

Thickness of housing pipe. Referring to Table 4.3, the thickness of the housing pipe may be taken as 3 mm.

Depth. Depth of housing pipe = Water table depth below ground level + Drawdown + Seasonal fluctuation + Allowance for submergence of pump.

Assuming the allowance for submergence to be 5.5 m and a clearance of 50 cm between pump and bottom of housing pipe, the depth of housing pipe is 15 + 5 + 1 + 5.5 + 0.5 = 27 m

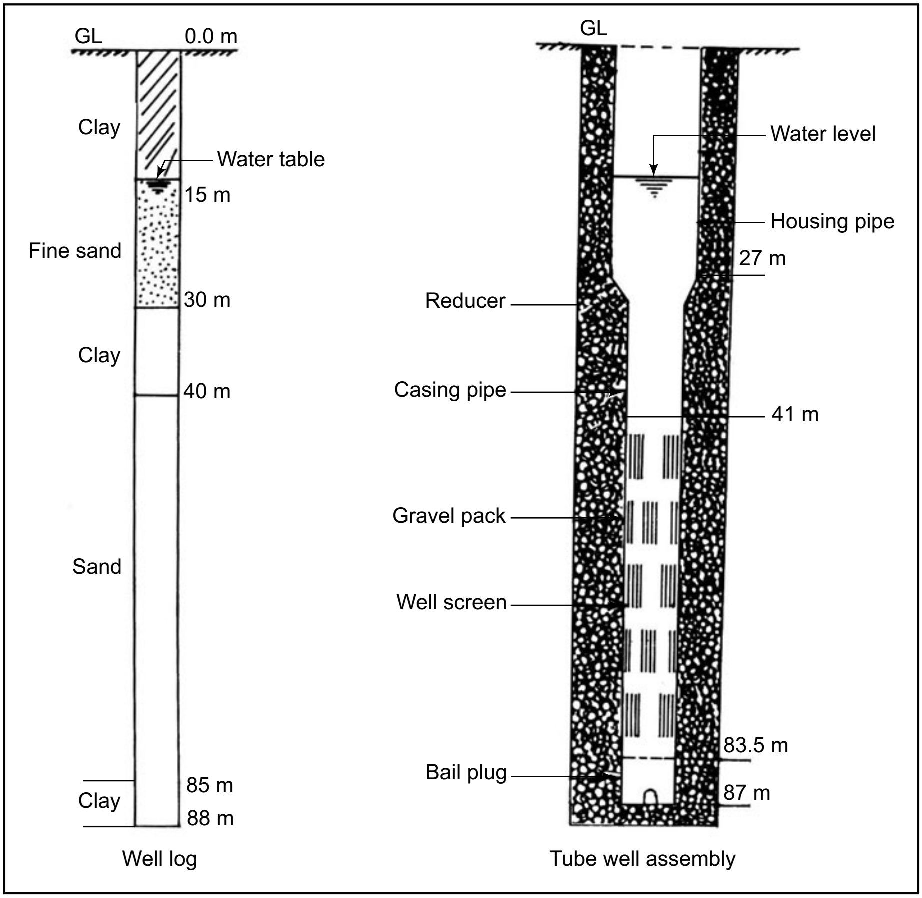


Fig. 4.24 Tube well pipe assembly to suit well log

(ii) Design of Well Casing Pipe

Diameter. Assuming a flow velocity of 3 m/s, for a discharge of 3000 1/min, the cross-sectional area of the casing pipe,

$$a = \frac{Q}{v}$$

$$Q = 3000 \text{ 1/min}$$

$$= \frac{3000}{60 \times 1000} \text{ cumecs}$$

$\therefore$

$$a = \frac{3000}{60 \times 1000} \times \frac{1}{3} = 0.0167 \, m^2$$

But

$$a = \frac{\pi}{4} d^2$$

or $$d = \sqrt{\frac{a \times 4}{\pi}}$$

$\therefore$ Diameter of casing pipe $= \sqrt{\frac{0.0167 \times 4 \times 7}{22}}$

$= 0.145 \text{ m} = 14.5 \text{ cm}$

However, referring to Table 4.5, the minimum diameter of casing pipe for a discharge of 3000 1/min is 20 cm. Hence, a plain pipe of 20 cm diameter is selected, which is higher than the calculated value.

Thickness. Referring to Table 4.4 for a 20 cm diameter, 87 m deep well, the thickness of a pipe is 1.98 mm. Hence, a thickness of 2 mm is selected.

(*iii*) *Design of Gravel Pack*

The grain size distribution curve of the aquifer material is given in Fig. 4.25. The grain sizes d_{10}, d_{50} and d_{60} are 0.12, 0.32, and 0.36 mm, respectively. The uniformity coefficient is 0.36/0.12 = 3. It is apparent that the aquifer cannot be developed naturally, and artificial gravel packing has to be provided.

The size of the gravel is determined by multiplying d_{50} size of aquifer by 12 and 15.5 (the two limiting values). Hence, d_{50} size of gravel used should lie between 0.32 × 12 = 3.84 mm and 0.32 × 15.5 = 4.96 mm. The d_{50} size of non-uniform aquifer material is indicated by point *A*. The lower and upper limits of the d_{50} size of gravel pack are shown by two points *B* and *C*, respectively. A line is drawn through point *B*, as explained earlier so that the C_u of gravel pack is less than 2. Another line through point *C* is drawn parallel to the line through point *B*. These parallel lines, define the zone in which the particle size distribution of the gravel should lie. The particle size distribution curve of the gravel pack is drawn by joining the bottom of the lower limiting-size curve to the top of the upper limiting curve. Referring to Fig. 4.25, the minimum size of gravel is found to be 3.6 mm and the maximum 5.6 mm.

Thickness of gravel pack. The thickness of the gravel pack provided may be 15 cm (Art. 4.4.3).

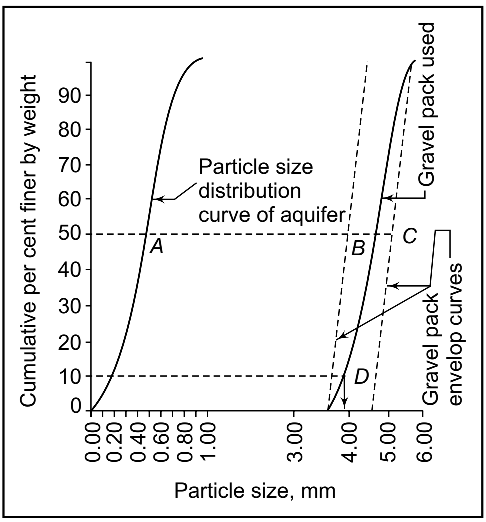


Fig. 4.25 Design of gravel pack and slot size for gravel pack tube well (Example 4.3)

(*iv*) *Design of Well Screen*

Slot opening. The slot size of the screen should be such that it retains at least 90 per cent of the gravel. The d_{10} size of the gravel pack is 3.9 mm. A slot size of 4 mm is selected.
Percentage of open area. The percentage open area of the screen may be adopted as 20 per cent (Sec. 4.4.5). The effective open area is 10 per cent.
Diameter of well screen. The diameter of the well screen is usually kept the same as that of the casing pipe. Hence, it may be kept as 20 cm.
Screen length. The effective area per metre length of the well screen is given by

$$A_o = \pi d \times \frac{10}{100} = \frac{22}{7} \times \frac{20}{100} \times \frac{10}{100}$$
$$= 0.063 \text{ m}^2$$

The screen length is estimated using Eq. (4.1). Assuming the entrance velocity to be 1.8 m/min.

$$h = \frac{3}{0.063 \times 1.8} = 26.45 \text{ m, say 27 m}$$

The aquifer thickness is 40 m. Therefore, it is desirable to provide about 36 m length of screen, which is more than 27 m and about 90 per cent of the aquifer depth. The screen may be provided in the central portion of the aquifer, leaving equal depths untapped at both ends. The design details are illustrated in Fig. 4.24.

4.5 SANITARY PROTECTION OF TUBE WELLS

Tube wells constructed for drinking water supply, should be protected against pollution. They should be located such that they are protected from the possible sources of contamination. At the same time, environmentally sensitive objects should be protected from the potential impacts of the tube wells. The recommended minimum distances are given in Table 4.7.

TABLE 4.7 Recommended Minimum Distance of the Tube Well

	Feature	Distance 'm'
(a)	**Possible Source of Contamination**	
	Garbage dumps/refuse piles	100
	Seepage pit or cesspool	50
	Pit toilets, animal sheds	30
	Septic tank, surface water body	15
(b)	**Environmentally sensitive objects**	
	Wetlands	500
	Archaeological important buildings	250
	Shrines and graveyards	100

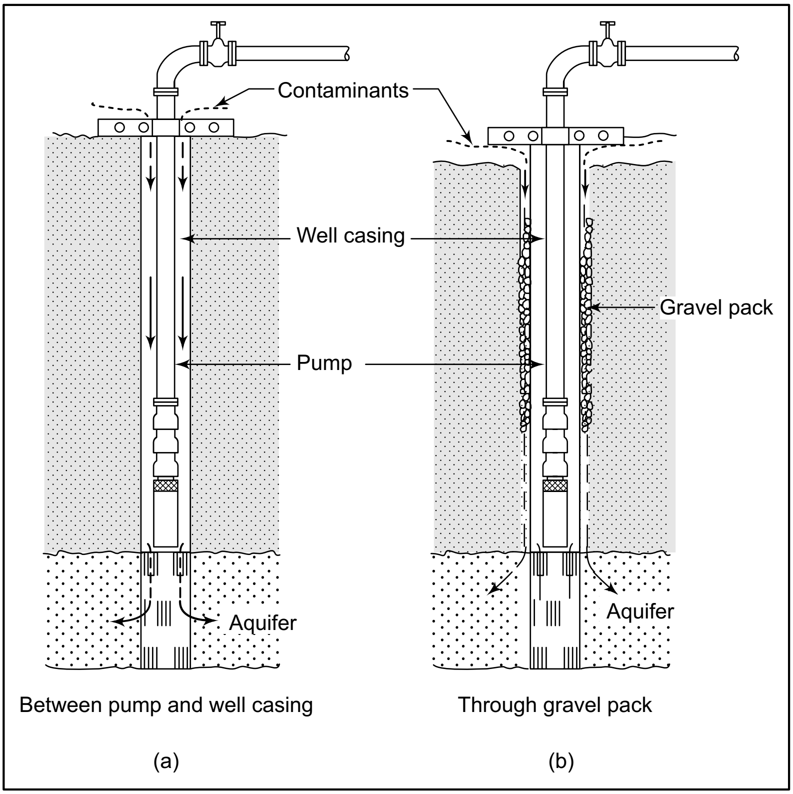
Source: NWFP (2004)

The general causes of pollution of shallow aquifers and the requirements of the locations of wells for sanitary protection, discussed in Ch. 3, apply equally to tube wells.

4.5.1 Common Causes of Contamination and Their Remedies

The following are the common paths of entry of contaminated surface water into the tube well:

1. *Between the pump and the well casing* (Fig. 4.26 a). The concentric space between the well casing and the pump often serves as a conduit for surface contaminants to enter the aquifer.
2. *Improperly placed gravel pack* (Fig. 4.26 b). The gravel pack is sometimes made continuous from the bottom to the ground surface, without any method of sealing at the surface. This provides a potential pathway for pollutants, unless proper well-seals are provided.
3. *Around the well casing* (Fig. 4.26 c). The disturbed zone immediately surrounding the well casing frequently offers a passage for surface contaminants.
4. *Reverse flow through the pump.* Open discharge pipes of pumps may sometimes serve as conduits for polluted water to contaminate ground water. This is experienced when there is ponding of surface runoff at the well.
5. *Subsidence of the soil or aquifer around the well casing due to sand pumping* (Fig.4.26 d). Subsidence results in the reversal of the ground slope in the vicinity of the well, destruction of masonry or concrete slabs around the well casing, and reduction in effectiveness of the cement-grout seal.



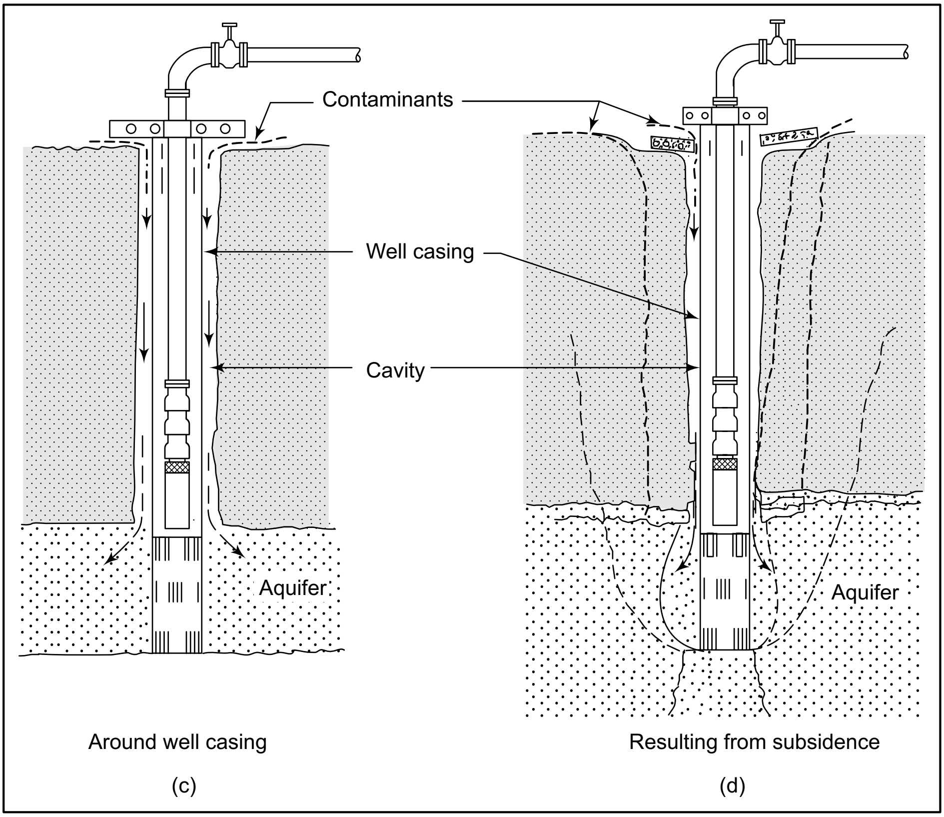


Fig. 4.26 Common paths of entry of contaminated water into the tube wells

In case of shallow tube wells penetrating unconfined aquifers, the source of contamination is almost exclusively surface water. However, when a tube well penetrates more than one aquifer, the well bore or gravel pack can act as a vertical conduit for the flow of water from one aquifer to another. In such a situation, one aquifer may get contaminated by another, even though the two are separated by an appreciable thickness of impermeable material (Fig. 4.27).

Protecting the Top Section of a Tube Well from Entry of Contaminants

The well casing should extend at least 30 cm above the surrounding land. At the ground surface, it is surrounded by a concrete slab or masonry floor, extending at least 60 cm in all directions (Fig. 4.28). The upper surface of the concrete slab and the surrounding land is made to slope away from the well so as to drain water away from the well. In addition, a sanitary well seal is provided at the top of the well to prevent the direct entry of contaminated water.

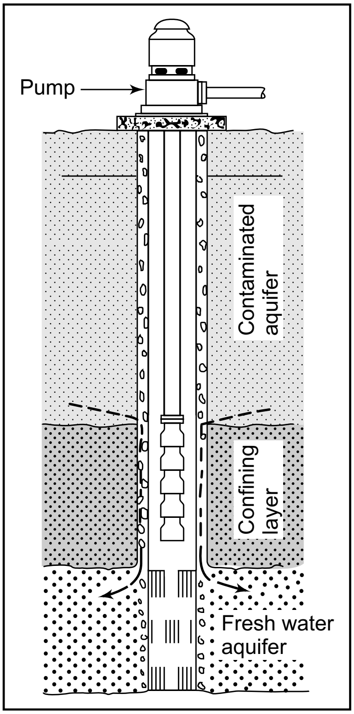


Fig. 4.27 Inter-flow from contaminated aquifer to fresh water aquifer through the gravel pack

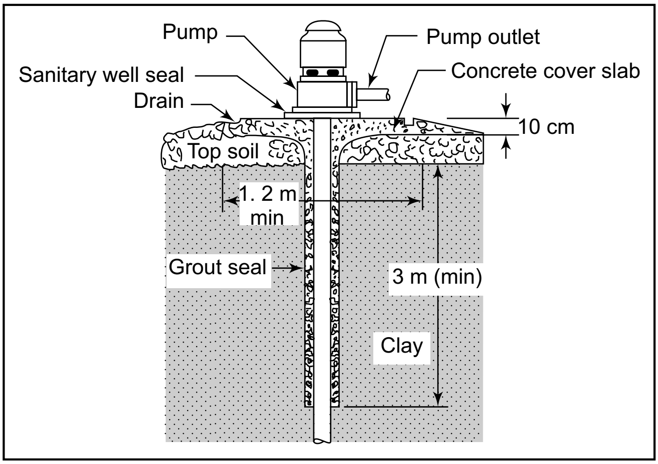


Fig. 4.28 Sanitary protection of the top section of a tube well

Grouting and Sealing of Well Casing

The drilled hole is usually larger than the well casing. This creates an irregularly shaped annular space around the well casing. It is essential to fill this space, in case of wells drilled for drinking water supply, so that the entry of contaminated surface water is stopped. It is also necessary to seal out water of unsuitable quality in strata above a fresh water aquifer.

In case of materials which cave-in, such as sand or sand and gravel, the annular space gets filled soon. In such cases, it may not be necessary to make any special efforts to fill in the annular space. Wherever the material overlying the aquifer is of the non-cave-in type, such as clay, the annular space should be grouted with a clay or cement slurry to a depth of 3 to 5 m below the surface (Fig. 4.29). In such cases, the diameter of the drilled hole is kept 7 to 15 cm larger than the well casing to facilitate the placing of the grout.

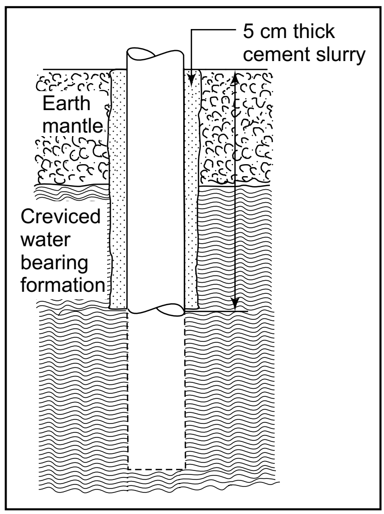


Fig. 4.29 Sanitary protection of bore wells drilled in hard rock formations with earth mantle less than 8 m thick

4.6 DESIGN OF SKIMMING WELLS

The design of skimming wells has been discussed in detail by Zuberi and McWhorter, (1973). The following design equations are used:

$$\dot{Q} = \frac{kQ}{\psi_\infty - \psi_{rw}} \tag{4.2}$$

where,

$$k = \frac{1}{2\pi \frac{\Delta\lambda}{\lambda_f}\left(1 + \frac{\Delta\lambda}{\lambda_f}\right)K} \tag{4.3}$$

$$\psi_\infty = \left(\frac{m}{1 + \frac{\Delta\lambda}{\lambda_f}}\right)^2 \tag{4.4}$$

$$\psi_{rw} = \left(\frac{m}{1 + \frac{\Delta\lambda}{\lambda_f}} - \xi\right)^2 \tag{4.5}$$

where, m = thickness of fresh water zone, m

λ_f = average specific weight of the upper fresh water layer, g/cm^3

K = permeability of the aquifer, m/s

$\Delta\lambda$ = difference in specific weight of fresh and saline water, g/cm^3

ζ = interface elevation relative to original position, m

$\dot{Q}$ = dimensionless discharge

Design graphs (Zuberi and McWhorter, 1973) have been developed using the following dimensionless parameters (Fig. 4.30):

1. Dimensionless penetration $\dot{d} = \frac{d}{m}$ (4.6)
2. Dimensionless rise of cone (of saline water) $\dot{\xi} = \frac{\xi}{m}$ (4.7)
3. Dimensionless discharge $\dot{Q} = \frac{kQ}{\psi_\infty - \psi_{rw}}$ (4.8)

4.6.1 Data Required

The following data are required for the design of skimming wells:

1. Thickness of fresh water zone, m
2. Average specific weight of the upper fresh water layer, λ_f

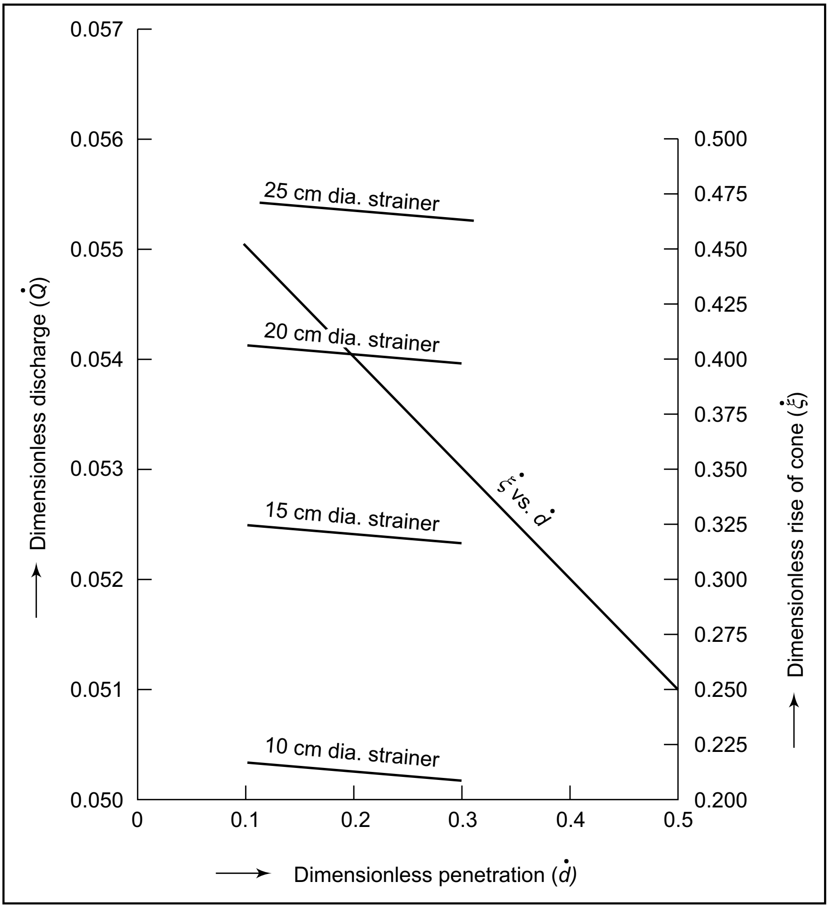


Fig. 4.30 Graphical solution for the design of skimming wells
Adapted from: Zuberi and McWhorter (1973)

3. Average specific weight of the underlying saline water, λ_b
4. Permeability of the aquifer, K
5. Specific yield of the aquifer, S_y

The step-by-step procedure for the design is explained in Example 4.4.

Example 4.4 Design a skimming well using the following data:

$$\lambda_f = 1.00 \text{ g/cm}^3$$
$$\lambda_b = 1.02 \text{ g/cm}^3$$
$$\Delta\lambda = 0.02 \text{ g/cm}^3$$
$$K = 0.001 \text{ m/s}$$
$$S_y = 0.14$$
$$m = 30 \text{ m}$$

The penetration may be assumed to be 20 per cent.

Solution

Using Fig. 4.30, for the dimensionless penetration $\dot{d}$ equal to 0.2, the dimensionless discharge and the dimensionless rise of the cone of saline water are obtained as follows:

$$\dot{Q} = \frac{kQ}{\psi_\infty - \psi_{rw}}$$

$$= 0.05043 \text{ for 10-cm diameter strainer}$$

$$= 0.05241 \text{ for 15-cm diameter strainer}$$

$$= 0.05402 \text{ for 20-cm diameter strainer}$$

and
$$\dot{\xi} = \frac{\xi}{m} = 0.4$$

$$\xi = 0.4 \times \text{m} = 0.4 \times 30 = 12 \text{ m}$$

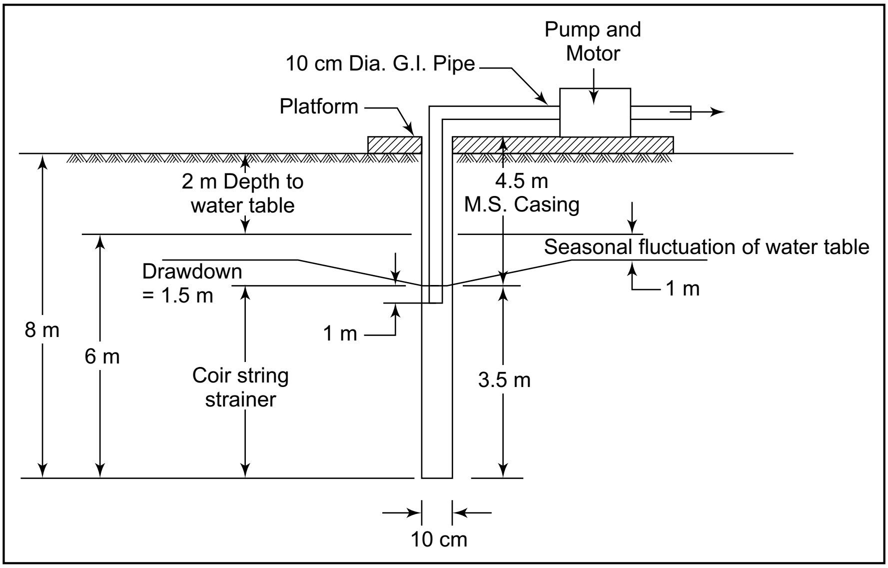


Fig. 4.31 Design of skimming well (Example 4.4)

Also,
$$k = \frac{1}{2\pi \dfrac{\Delta\lambda}{\lambda_f}\left(1 + \dfrac{\Delta\lambda}{\lambda_f}\right)K}$$

$$= \frac{1}{2\pi \dfrac{1}{50} \times \dfrac{51}{50} \times 0.001} = 7805.7 \text{ s/m}$$

$$\psi_\infty = \left(\frac{m}{1 + \dfrac{\Delta\lambda}{\lambda_f}}\right)^2 = \left[\frac{30}{51/50}\right]^2 = 865 \text{ m}^2$$

$$\psi_{rw} = \left(\frac{m}{1+\dfrac{\Delta\lambda}{\lambda_f}} - \xi\right)^2 = (29.41 - 12)^2 = 303 \text{ m}^2$$

$$\therefore \qquad \frac{\psi_\infty - \psi_{rw}}{k} = \frac{865 - 303}{7805.7} = 0.072$$

For a 10-cm diameter strainer,

$$Q = 0.05043 \times \frac{\psi_\infty - \psi_{rw}}{k}$$

$$= 0.05043 \times 0.072 = 0.0036 \text{ m}^3/\text{s}$$

$$\text{Penetration depth} = 30 \times \frac{20}{100} = 6 \text{ metres}$$

Assuming a seasonal fluctuation of one metre and drawdown of 1.5 m, a 10-cm diameter strainer, 3.5 m long (6.00 – 2.5) may be used.

The designed well is shown in Fig. 4.31.

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SHORT QUESTIONS

I. State True (T) or False (F).

1. Strainer-type screens are suitable in water bearing formations mainly comprising of coarse sand and gravel particles.
2. Continuous-slot type screens are least efficient hydraulically.
3. The tube wells with coir rope strainer can be developed by air compressor.
4. The durability of bambo strainer is reduced by micro-organisms.
5. Slotted-pipe well screens are used with gravel pack around them.
6. The minimum spacing between slot should be 1.6 mm.
7. The bail plug is fitted at the bottom end of well screen.
8. In Jetted tube wells the hole in the ground is made by cutting action of stream of water.
9. Well point is fitted on top of the driven tube wells.
10. In semi-artisian well, the water flows out of the well.
11. Skimming wells are used to skim brackish water underlain with good quality water in the upper layer.
12. Battery of wells or well point system can be used synonymously.
13. Radial wells are used to tap deeper ground water.
14. Infiltration galleries are used to tap shallow ground water.
15. In radial collector wells, series of horizontal wells discharge water into a caisson.
16. Shrouding is not gravel packing.
17. The collapse strength of PVC well screen is usually in the range of 50 to 70 per cent that of casing pipes of identical size.
18. Agricultural strainer and bambo strainer are adapted to similar conditions.
19. Coir strainers are ideal for deep tube wells.
20. In pre-pack filters gravel grains are bounded together with water-proof chemicals.
21. Pre-pack filters have a high permeability.
22. Effective size of particles is designated by d_{90}.
23. The value of uniformity coefficient for one grain size is one.
24. For heterogeneous sand the value of uniformity coefficient will be low.
25. Housing pipe is enlarged section of well casing provided at the bottom of the well.
26. Diameter of well casing pipe is selected to obtain a velocity of water of 2.5 – 3 m/s.
27. The thickness of well casing pipe increases with increase in diameter.
28. The thickness of casing pipe is independent of depth of well.
29. Deep tube wells draw their supplies mainly from the unconfined aquifers.
30. In case of gravel-pack type well, the minimum bore size should be thickness of the gravel pack plus the outside diameter of the casing pipe.
31. The thickness of gravel pack should not be less than 7.5 cm.
32. The depth of a well is determined from the well log.
33. If two sand samples have the same effective size, the sample with a lower value of uniformity coefficient will be less permeable.
34. In case of confined aquifer it is desirable to provide the screen in the lower 1/3rd thickness.
35. The size of the slot openings in well screen is governed by the yield of the tube well.

36. For a homogeneous formation with non-corrosive water, the size of the screen opening should retain 40 per cent of sand.
37. It is desirable to provide an area of about 20 per cent for well screens.
38. The permissible entrance velocity through the effective open area of the screen should be more than 5 cm/s.
39. The gravel pack increases the permeability between the screen and the aquifer.
40. Gravel pack does not help in providing support to the formation.
41. Gravel pack is recommended in aquifers having uniformity coefficient of 2 or less.
42. Limestone in gravel pack is not desirable.
43. To protect drinking water supply against pollution, the minimum distance of the tube well from garbage dumps should be 100 m.
44. Conditions for growth and survival of bacteria and viruses in ground water are generally favourable when compared with surface waters.
45. Wells can allow direct contamination of an aquifer due to inadequate grouting or seals.
46. During the drilling of new tube wells, contamination could be introduced into the tube wells.
47. Corrosion is usually lowest at points of contact of different metals.
48. Ground water produced by wells must be tested regularly to ensure safe drinking water.
49. Clear water is always safe to drink.
50. The chemical characteristics of water usually change considerably when it comes in contact with underground mineral deposits.
51. Water sample passing bacteriological test indicates proper disinfection.

Ans. True: 1, 4, 5, 7, 8, 12, 14, 15, 17, 18, 20, 21, 23, 26, 27, 31, 32, 36, 37, 39, 41, 42, 43, 45, 46, 48, 50, 51.

II. Select the correct answer.

1. For an efficient well, the per cent open area of well screen should be
   (a) less than 5 per cent (b) 5–10 per cent
   (c) 15–20 per cent (d) about 25 per cent
2. To keep the sand movement and head losses to a minimum the entrance velocity through individual well screen opening should be between
   (a) 3–7.5 cm/sec (b) 10–15 cm/sec
   (c) 15–20 cm/sec (d) 20–25 cm/sec
3. The lower limit for thickness of artificial gravel pack is
   (a) 5.0 cm (b) 7.5 cm
   (c) 10.0 cm (d) 12.5 cm
4. Gravel packing is required in an aquifer with uniform coefficient
   (a) less than 2 (b) between 3 and 4
   (c) between 5 and 6 (d) more than 6
5. In case of homogeneous water table aquifer the portion of aquifer to be screened is
   (a) entire (b) lower one half
   (c) top one third (d) bottom one third
6. The diameter of driven tube wells usually vary from
   (a) 3–7.5 cm (b) 7.5–12.5 cm
   (c) 12.5–15 cm (d) 15–20 cm

7. The diameter of the pipe of well section below the pump housing is fixed by velocity of water through the pipe of the order of
   (a) 2.5–3 m/s (b) 4.5–5 m/s
   (c) 5–6 m/s (d) 6–7 m/s
8. To facilitate the lowering of the pipe, the bore of the tube well should be more in diameter than casing pipe by at least
   (a) 2.5 cm (b) 5 cm
   (c) 7.5 cm (d) 10 cm
9. For a homogeneous aquifer with non corrosive water the size of screen opening taken is one that will retain
   (a) 20 per cent of sand (b) 30 per cent of sand
   (c) 40 per cent of sand (d) 50 per cent of sand
10. Collector wells are also called
    (a) radial wells (b) cavity wells
    (c) infiltration galleries (d) artesian wells
11. Gravel packed wells are constructed when effective diameter of aquifer material is
    (a) less than 0.25 mm (b) 0.25–0.5 mm
    (c) 0.5–0.75 mm (d) more than 0.75 mm
12. To retain 90 per cent of gravel pack materials, the slot size of screen should be equal to
    (a) d_{90} of pack material (b) d_{60} of pack material
    (c) d_{50} of pack material (d) d_{10} of pack material
13. An aquifer with $C_u \leq 2$ is called
    (a) uniform (b) non-uniform
    (c) isotropic (d) homogeneous
14. Uniformity coefficient, Cu is the ratio between
    (a) d_{10}/d_{60} (b) d_{60}/d_{10}
    (c) d_{90}/d_{40} (d) d_{40}/d_{90}
15. If the piezometric surface of a confined aquifer decline to a level below the top of the aquifer, the aquifer is then called
    (a) unconfined aquifer (b) perched aquifer
    (c) leaky aquifer (d) artesian aquifer
16. SDR is the ratio between
    (a) diameter of the pipe and its thickness
    (b) thickness of the pipe and its diameter
    (c) diameter of the pipe and its length
    (d) length of the pipe and its thickness
17. The minimum diameter of the housing pipe should be more than the nominal diameter of submersible pump by
    (a) 2.5 cm (b) 5 cm
    (c) 7.5 cm (d) 10 cm
18. The depth of housing pipe is selected such that the pump is
    (a) partially submerged in water (b) on the ground surface
    (c) always submerged in water (d) always above the water table

19. The average life of bamboo strainers is
    (a) 5 to 6 years (b) 8 to 10 years
    (c) 13 to 15 years (d) 20 years
20. Louver type screen have opening in the form of
    (a) rectangular slots (b) round opening
    (c) shutters (d) continuous slot
21. The minimum distance of the tube well from garbage should be
    (a) 25 m (b) 50 m
    (c) 75 m (d) 100 m
22. The most suitable well screen in case of aquifer formations having a mixture of fine and coarse particles is
    (a) slotted pipe (b) agricultural strainer
    (c) louver–type screen (d) continuous slot type screen
23. A battery of multiple well is adapted under the conditions where
    (a) water table is deep
    (b) cavity formation is not possible
    (c) thickness of aquifer is limited
    (d) hydraulic characteristics of the aquifer are very good

Ans. 1 (c) 2 (a) 3 (b) 4 (a) 5 (d) 6 (a) 7 (a) 8 (b)
9 (c) 10 (a) 11 (a) 12 (d) 13 (a) 14 (b) 15 (a) 16 (a)
17 (b) 18 (c) 19 (a) 20 (c) 21 (d) 22 (a) 23 (c)

5

Tube Well Construction

Tube well construction involves three distinct operations. These include drilling the bore hole, installing the casing and well screen, and developing the well to ensure sand-free operation at maximum yield. Where artificial gravel packing is required, the operation is considered part of well-screen installation. The first two operations are discussed in this chapter. Well-development procedures are described in Ch. 6.

Tube wells may be bored, jetted, driven or drilled. A bored well is one in which excavation is carried out by means of hand or power augers. In a jetted tube well, excavation is done with a high velocity jet of water. A driven well is constructed by driving a pointed screen into the ground and adding casing pipes to the drive point as it is being driven into the ground. In a drilled well, excavation is done either by percussion or rotary drills. Each method of construction has its own advantages and adaptability.

5.1 CONSTRUCTION OF BORED AND DRIVEN TUBE WELLS

Boring, driving and jetting are usually adopted for constructing small-sized wells used in domestic water supply in regions with alluvial formations.

5.1.1 Bored Wells

Boring is commonly done by means of an earth auger turned by hand (Fig. 5.1). Power augers are also sometimes used. Boring is adopted to situations where ground water is at shallow depths and where the requirement for water is not high. Hand augers can be used to penetrate clay, silt and some sand, where the open hole will be able to stand upto depths of 7–10 m. The size of the hole may vary from 5–50 cm.

Boring is done by spiral or worm augers. The hand auger consists of a shaft or pipe, with a wooden handle at the top and a bit with curved blades at the bottom (Fig. 5.1). It is provided with shaft extensions and couplings. Boring is started by forcing the blades of the auger into the soil, while turning the tool. When the space between the blades is full of soil, the auger is lifted and emptied. The operation is repeated until the hole is bored to the required depth. Sometimes, during boring, stones or boulders may be encountered which will prevent further penetration. In such situations, a spiral, also called a rams-horn, is used to fish out the obstruction. The spiral is turned in a clockwise direction. It will turn around the stone or boulder, which can be lifted to the surface. The regular auger is then replaced and boring continued.

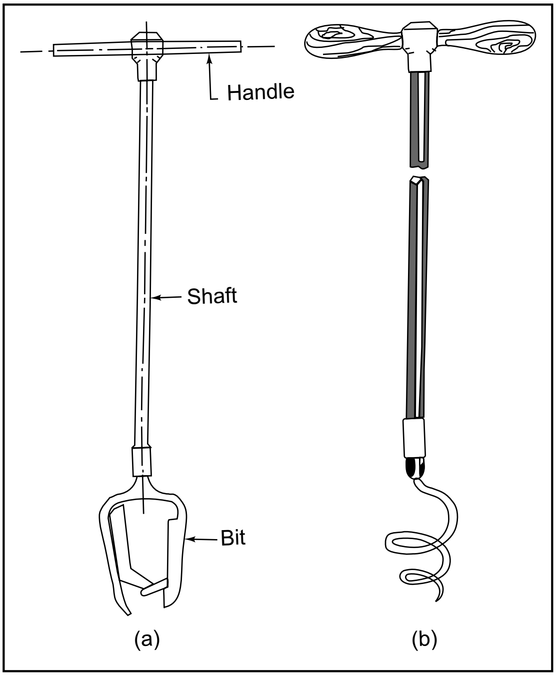

Fig. 5.1 Hand boring equipment: (a) Hand auger, (b) Spiral

Wells upto 4 to 5 m can usually be bored without the use of a tripod. For larger depths, a tripod with a pulley block at the top is provided to insert larger auger rods into the hole and remove them without damage.

Power augers are used to bore wells of 20–80 cm diameter. The augers are rotated, raised and lowered by power-driven mechanisms.

Bored wells are completed by installing well screens in the water-bearing formation and developing the well, as explained in Ch. 6.

5.1.2 Driven Wells

Small diameter driven wells are constructed by driving a well point into the ground. The well point consists of a perforated pipe, with a steel point at its lower end to break through pebbles or thin, hard layers. It is driven deep into the shallow water-bearing formation. The depth of driven well does not ordinarily exceed 7 m and their diameters vary from 4–5 cm. Sections of pipes 1.5 to 1.8 m in length are added to the top of the well point to serve as the casing of the completed well.

Well Points

Well points are of various types and sizes. The commonly used ones are the continuous-slot type, brass-jacket type, brass-tube type, mesh-covered type and slotted-pipe type. The continuous-slot well point has a screen with horizontal openings. It is a one-piece welded construction, without any internal perforated pipe. It can withstand hard driving. The brass-jacket-type well screen consists of a perforated pipe wrapped with wire mesh. The mesh is covered with a perforated brass sheet. The pipe body of the brass jacket should be strong enough to withstand the force exerted while driving the pipe into the ground. A brass-tube type well point consists of a brass tube slipped over a perforated steel pipe. It has a more rugged construction than the others described above.

All well points have forged or cast-steel point bottoms and pipe-shank tops. For mesh-covered well points, the sizes of opening are designated by the mesh size. The common mesh sizes are 16, 20, 24, 28 and 32-mesh (number of meshes per cm length). For well points with slot openings, the slot sizes are designated by numbers that correspond to the actual width of openings. Well points may also be made of PVC (Fig. 4.18).

Construction of Driven Wells

Driven wells are generally started in holes bored with hand augers. The diameter of the hole should be a little larger than that of the well point. The hole should be made as deep as the auger can work. Pipe joints should be screwed tightly after the threads are carefully cleaned and oiled. White lead or joint compound could be used to improve air-tightness. Protection of the threads by caps or couplings, during transportation and storage, is desirable.

It is essential that the well pipe is kept vertical. If the pipe is not exactly vertical during the early part of driving, it may be straightened by pushing while blows are delivered. If it cannot be straightened, it is withdrawn and started again at a new place.

Driving Methods

Driving may be done by using a maul or sledge hammer to strike directly on a drive cap fitted to the well pipe (Fig. 5.2). The drive cap protects the top of the pipe during the driving operation. After each length of pipe is driven into the ground, the cap is removed and additional sections are attached and driven, as required. The pipe is kept full of water at all times. In its descent through the subsoil, the well screen is sealed by the formations through which it travels. But, as the well point comes in contact with a water-bearing sand or gravel, some water flows out and the water remaining in the pipe drops to its static level. This is a signal to the driller that the water-bearing layer has been reached. A reciprocating-type pump is used to develop the well. Considerable amounts of sandy water may be pumped for a short time but if a good water-bearing strata has been tapped, continued pumping will result in clear, sand-free water.

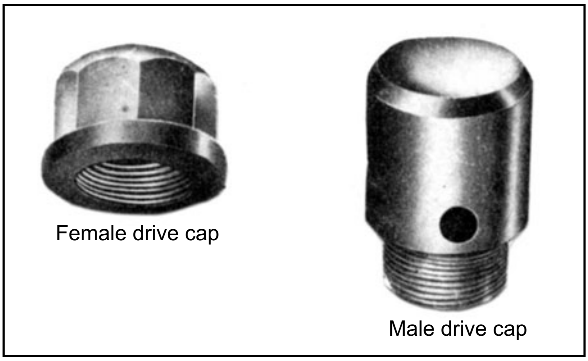

Fig. 5.2 Types of drive caps used in driven wells
Source: U.S. Dept. of Army and Air Force Tech. Manual (Anon, 1957)

Another method of driving is to employ a steel driving bar (weight) attached to a rope. The bar falls freely inside the pipe and strikes the base of the well point/casing pipe. This is one of the safest methods of driving because it does not weaken the pipe. A variation of the falling weight method is applied by using a drive monkey. A drive monkey is a weight that slides over the pipe (Fig. 5.3) and strikes on a drive cap. A tripod is employed whenever a drive monkey is used in driving the well point. In soft formations the rate of descent may be 5–7 cm per blow. Driving in sand or compact clay is facilitated by introducing water in the pipe or around it. Compact clay is difficult to penetrate.

Removing the Pipe

Well points and pipes can be withdrawn by upward blows by a drive monkey striking a pipe clamp or pipe puller head, or by a chain wound around the drive pipe and connected to a long lever operating against a solid fulcrum. Rotation of the pipe by wrenches will assist in its removal. After the pipe has been raised a few metres, it can be lifted by hand.

Limitations of Driven Wells

The main disadvantages of driven wells are (i) the slow progress in compacted soils, (ii) damage to well screens (well points are frequently stripped of mesh) and bent or broken pipes, (iii) air leak in joints due to broken couplings, and (iv) low yield.

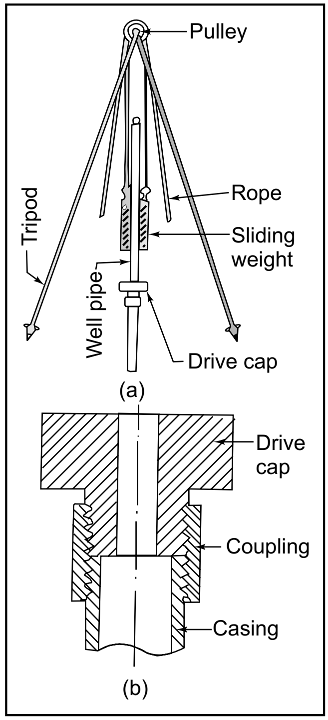

Fig. 5.3 Drive monkey arrangement for driving shallow tube wells: (a) Tripod, pulley and weight, (b) Section through drive cap (Enlarged view)

5.2 TUBE WELL DRILLING EQUIPMENT AND METHODS

Different types of tube well drilling rigs are used to suit the widely varying underground formations. Water well drilling equipment can be classified into three major groups: (i) percussion (cable tool) drills, (ii) rotary drills (including direct rotary, reverse rotary and air rotary), and (iii) down-the-hole hammer drills.

The cable tool drilling method has been employed for water well drilling since the twelfth century A.D. In this system, the drilling operations are carried out by lifting and dropping a heavy string of tools regularly in the bore hole. No fluid is circulated in the hole. The drill bit breaks or crushes the formation into small fragments and drill cuttings are subsequently bailed out by adding water.

In the rotary method, the formation is cut by means of a rotating bit and the cutting lifted by circulation of a drilling fluid, as the bit penetrates. The down-the-hole drilling method combines the percussive action of percussion drilling and the rotary action of rotary drilling. The tool is essentially a pneumatic hammer attached to the end of a drill string.

On the basis of the capacity rating, drilling rigs may be divided into three broad groups, namely, shallow, medium and heavy. Under each group they can be classified further on the basis of their diameter and depth of the hole, which could be drilled with the equipment. Table 5.1 presents a commonly used classification of drilling rigs.

TABLE 5.1 Classification of Drilling Rigs

Type of drilling rig	Classification	Limiting diameter of hole, mm	Depth of hole, m	Size of drill rods, mm
Percussion	Light	130	< 50	—
(Cable tool)	Medium	200	50–170	—
	Heavy	200	> 170	—
Direct rotary	Light	200	0–250	73
	Medium	200	251–457	73–89
	Heavy	200	> 457	89
Reverse rotary	Light	500	< 170	150
	Medium	675	> 170	150
Combination	Light	—	—	—
(Rotary-cum-	Medium	200	< 500	89
percussion)	Heavy	300	> 500	89
Down-the-hole	Light	114	< 50	89
(DTH hammer)	Medium	150	50–170	114
	Heavy	200	> 170	114

Source: Das (1983)

5.2.1 Drilling Methods

Drilling methods are classified on the basis of the type of drilling equipment used for constructing the tube well. The classification of commonly used drilling methods is given below:

1. Percussion drilling
   (a) Hand boring
   (b) Mechanical boring (standard cable tool method)
2. Hydraulic rotary drilling
   (a) Direct circulation hydraulic rotary drilling
   (b) Reverse circulation hydraulic rotary drilling
   (c) Dual wall reverse circulation hydraulic rotary drilling
3. Down-the-hole and air rotary drilling
4. Miscellaneous drilling methods
   (a) Jetting
   (b) Core drilling
   (c) Calyx drilling
   (d) Sonic drilling

5.3 PERCUSSION DRILLING

In percussion drilling, the well bore is formed by the percussive and cutting actions of a drill bit that is alternatively raised and dropped. The operation breaks the underground formations into fragments. The reciprocating motion of the drilling tools mixes the loosened material into a sludge, which is removed from the hole at intervals by bailer or sand pump. Simultaneously, casing pipes are lowered to prevent the cave-in of the material into the bore and permit continuous drilling. Percussion drilling can be used with manual labour (hand boring) or power rigs (standard cable tool method).

5.3.1 Hand Boring

Hand boring is extensively used in the construction of shallow tube wells in unconsolidated underground formations.

Equipment for Hand Boring

The hand boring set (Fig. 5.4) is a simple, manually operated outfit that works on the percussion principle. The equipment comprises a tripod, crab winch, bailers or sand pumps, cutter shoes, loading arrangement for sinking pipes, chain wrenches, pulley blocks, flexible steel wire rope, and tools such as spanners and wrenches. The bailer/sand pump normally acts as the drilling tool. It is a steel pipe of about 6 mm thickness, provided with a cutting edge at its lower end and a hook at the upper end. A flap valve is fitted inside the bailer, just above the cutting sleeve. A winch helps in winding and unwinding the wire rope when boring is in progress. The boring pipes are of mild steel and provided with suitable joints.

Three types of joints are usually used in joining boring pipes: (i) flush joints, (ii) swelled and cressed joints, and (iii) socketed joints (Fig. 5.5). Casing pipes with flush joints are easy to lower and withdraw, but require thicker pipes for the same strength. The lowest length of casing pipe is fitted with a cutter shoe at the bottom, which is slightly bigger in diameter than the casing pipe itself. This facilitates easy installation of boring pipes and their subsequent withdrawal after completion of boring and installation of well casing pipes and screens.

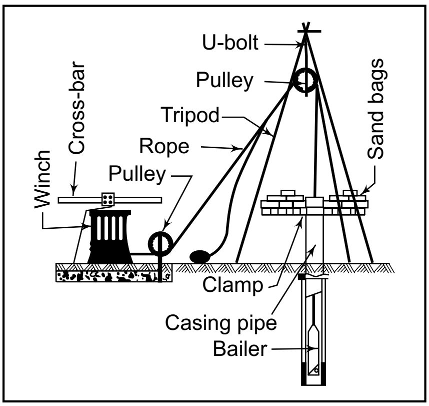

Fig. 5.4 Schematic view of a manually operated percussion drill for constructing shallow tube wells

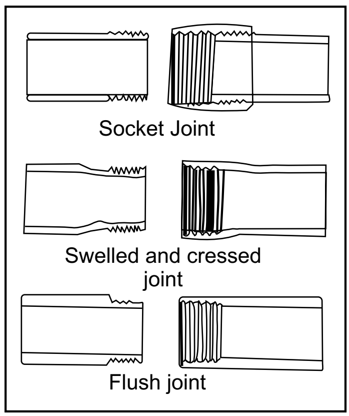

Fig. 5.5 Types of joints for boring pipes (4 threads/cm in all joints)

Auger Bits for Hand Boring

Hand boring sets are often equipped with augers (Fig. 5.6) to make shallow holes, especially in boring to install filter points. Augers of different shapes and sizes are made for the purpose. They are used to loosen and remove soil material. The auger is turned into the hole until loaded and then withdrawn and cleaned. The hole is bored until cave-in formations are encountered or a good water bearing formation is reached. Augers are not suitable for drilling in water bearing sand and gravel, as these have a tendency to wash down the hole. Auger holes can be drilled to shallow depths in unconsolidated formations, which can normally be started without a casing pipe.

Fig. 5.6 Setting aside the drill bit before using the bailer in percussion drilling
Courtesy: Television Kendra, Patna, Bihar

Hand Boring Procedures

A schematic sketch illustrating the hand boring method of well construction is shown in Fig. 5.4. A pit, about 2-2.5 m in dia. and 2 m deep, is dug at the site. A hole, 1 m deep, and of diameter slightly greater than the bore, is drilled, using an auger. A boring pipe is lowered into the bore hole with the help of a tripod. After lowering the first pipe partly in the hole, it is held in position with clamps and loaded with sand bags (Fig. 5.7). It is then partly filled with water. Boring is continued by operating the bailer, which is suspended with a wire rope passing over a pulley fixed to a tripod stand. The legs of the tripod should be buried in the ground in order to prevent their slipping or tilting. The wire rope passing over the pulley is tied to a winch so that it can be wound or unwound, as required, for lowering and raising the bailer.

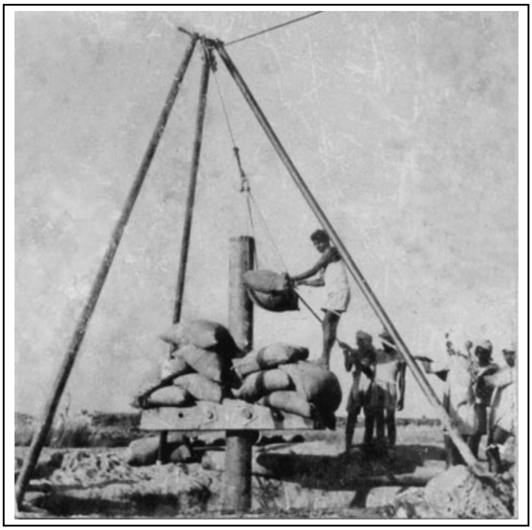

Fig. 5.7 Loading of sand bags on wooden clamps to lower casing pipes in a manually drilled tube well

The tripod is so fixed that the bailer is positioned centrally over the boring pipe. The bailer is operated vertically up-and-down in the boring pipe. Water is poured into the boring pipe from the top until the water table is reached. A slight circular motion is automatically imparted to the bailer by the torsion in the wire rope. During the downward stroke, the flap valve of the bailer is forced open and the loose material pounded at the bottom of the bore enters the bailer. As the upward stroke begins, the flap valve is closed and the material inside retained. After about 30 to 40 strokes, the bailer is lifted out of the boring pipe by winding the rope on the winch, and the loose material is emptied. The material brought up by the bailer is a sample of the stratum encountered during drilling. Boring is continued and additional casing pipes lowered, till the required depth of the well is reached.

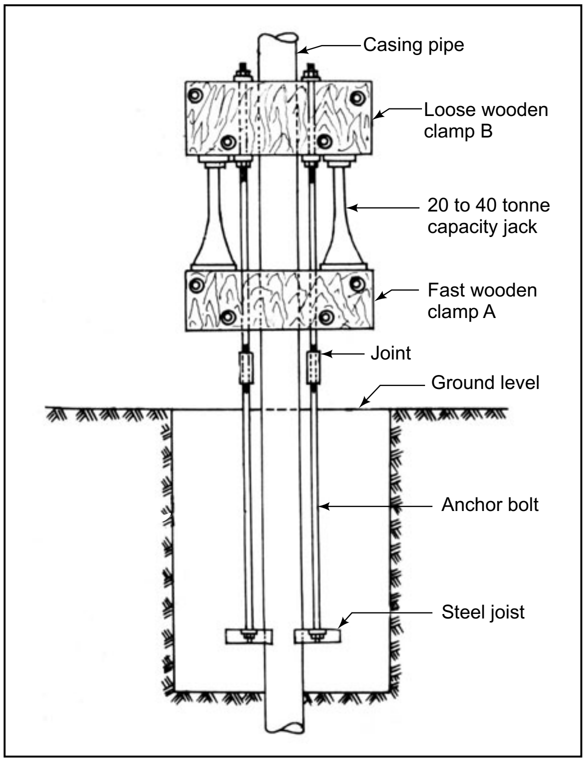

Fig. 5.8 Anchor bolt system of sinking casing pipes in percussion drilling

Anchor Bolt Method of Sinking Boring Pipes

An improved method of sinking boring pipes is by means of screws or hydraulic jacks (Fig. 5.8). The jacks are made to work against a wooden clamp *A*, which is fastened rigidly to the pipe, and with another wooden clamp *B*, fitted loosely around the pipe and held rigidly in position by means of two bolts which are securely anchored a few metres below ground level (Fig. 5.8). The anchor bolts consist of two mild steel rods of about 4 cm diameter and 5 m length. They are positioned on opposite sides of the pipe, at a distance of about 10 cm each from the pipe. The rods pass freely through the rigid clamp *A*, but are bolted firmly to the loose clamp *B* at their top. At the lower end, each rod is fastened by means of nuts on either side to two pieces of steel joists of about 1.2 m length, to serve as anchors. The joists are placed in the form of a cross in a dug pit, which is subsequently filled up. As the jacks are operated, clamp *B*, held rigidly by the anchor bolts, remains stationary while clamp *A* moves down along with the pipe. After the pipe has sunk some distance, clamp A is moved up on the pipe and the jack readjusted. The process is repeated, sinking the pipe a few metres each time.

Adaptability of Hand Boring Method

Hand boring is a simple and low cost method of tube well construction. It does not require any sophisticated equipment. Strata sampling is accurate. Hence, the method can also be used for test boring. Very little water is required for boring, which makes it suitable for well construction in remote areas.

Manually Operated Percussion Drilling Equipment for Installation of Hand pumps in Alluvial Formations

Simple percussion drilling equipment is used for installing hand pumps in alluvial formations. The equipment consists of a tripod stand, winch, pulley block, line pipes and wooden clamps (Fig. 5.9). Initially, a shallow hole is dug manually. Then, a line pipe with a drive-shoe fitted at the lower end is lowered. The line pipe is lifted and dropped in the bore hole. During the upward lift, the operator closes the upper end of the pipe with his hand, thus creating a vacuum in the pipe. The cuttings are sucked in gradually and rise in the column pipe at every upward and downward stroke, finally spilling over the top end of the pipe. The operation is continued till the required depth of well is reached. The pipe is then removed and lowered again with the required length of strainer. This method is suitable for bores of 3 to 4 cm diameter upto a depth of 30 to 50 metres for the installation of hand pumps under situations when the static water level is within the suction limit of 5–6 metres from the ground surface.

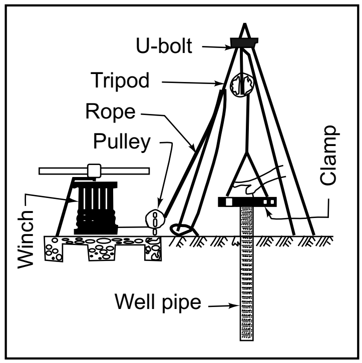

Fig. 5.9 Manually operated boring kit for installing hand pump

5.3.2 Mechanical Percussion Boring

Mechanical percussion methods of drilling tube wells are commonly known as cable tool drilling. As in hand boring, drilling is accomplished by operating the tools in up-and-down motions. The drill bit breaks or crushes the hard formations into small fragments. When working in soft, unconsolidated rocks, the drill bit loosens the material. In both cases, the reciprocating action of the tools mixes the crushed or loosened particles with water to form a slurry or sludge. The necessary water to form the slurry is added to the bore hole, if no water is present in the formations being penetrated. The resulting slurry is removed at intervals from the bore hole by means of a sand pump or bailer. Accumulation of sludge slows down the movement of the tools and hence the penetration. This factor usually determines the frequency of bailing of the sludge from the well.

Equipment for Cable Tool Percussion Drilling

The standard equipment for cable tool drilling consists of a portable rig (Fig. 5.10) mounted either on a truck chasis or on a trailer. The standard percussion rig consists essentially of (a) a mast (derrick),

Fig. 5.10 A truck-mounted heavy duty percussion drilling rig in transport position
Courtesy: Garlic & Co. Ltd., Mumbai

(b) a two-or three-line hoist, (c) a spudder for raising and dropping the tools, and (d) a diesel engine to provide power for the various operations (Figs. 5.11 and 5.12). In a 3-line hoist, one line (the drilling reel) is used for operating drilling tools, the second (the sand reel) for operating bailer/sand pump, and

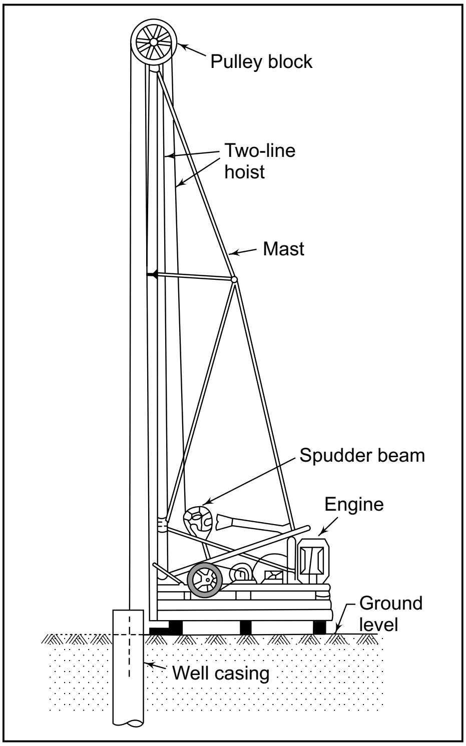

Fig. 5.11 Basic components of a percussion drilling rig

the third (the casing reel) for operating boring pipes. The mast is made long enough to allow the longest string of tools/pipes to be hoisted out of the hole, the minimum height being about 10 m. The mast is telescoped to its shortest length and folded at the top of the machine during transit. The reels have to be large enough to hold sufficient cables for drilling the deepest holes. The rig is capable of drilling and is strong enough to handle the drilling and fishing tools and other equipment. The drilling process includes three types of operations: (a) making the hole, (b) bailing out drilled cuttings, and (c) casing the bored hole. These three operations generally follow one after the other, till the bore is completed.

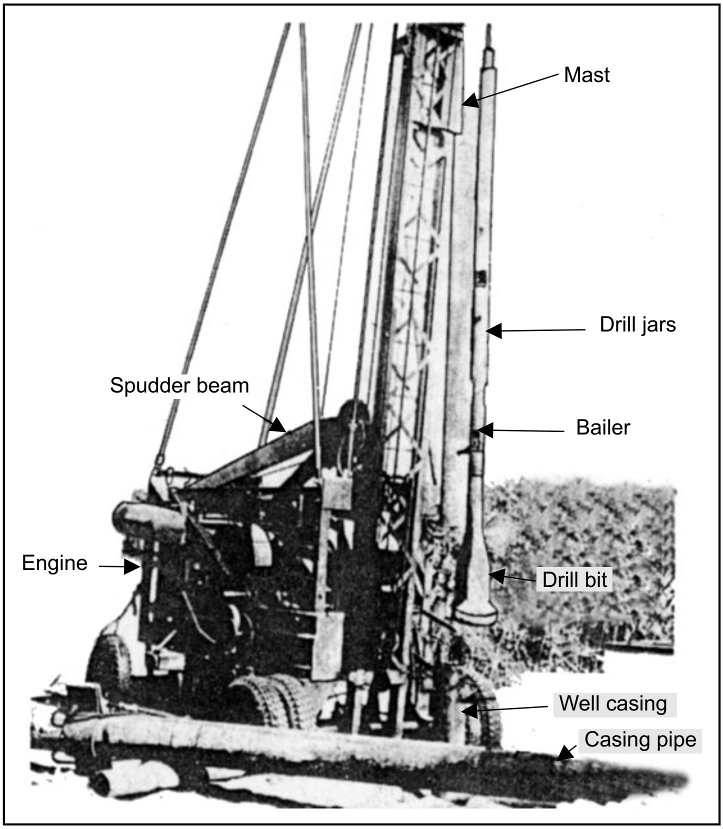

Fig. 5.12 An engine operated percussion drilling rig. The string of tools is seen to the right of the mast

A full string of tools, in ascending order consists of a drill bit of suitable type, a drill stem, jars and a swivel socket which is attached to the cable (Fig. 5.13). The drill stem gives additional weight to the bit and the effect of its added length helps maintain a straight hole when drilling in hard rock. The jars consist of a pair of linked steel bars. The rope socket connects the string of tools to the cable. In addition, its weight supplies part of the energy of the blows by the jars. It allows the tools to rotate slightly with respect to the cable.

Drill Bit

The drill bit (Fig. 5.14), which does the actual drilling, is the most important part of the string of tools. It consists of the cutting edge (Fig. 5.15), body, wrench, square shank and pin. The bit is not allowed to wear down below gauge size. This is particularly important when drilling in hard formations, since the diameter of the hole decreases as the bit wears down.

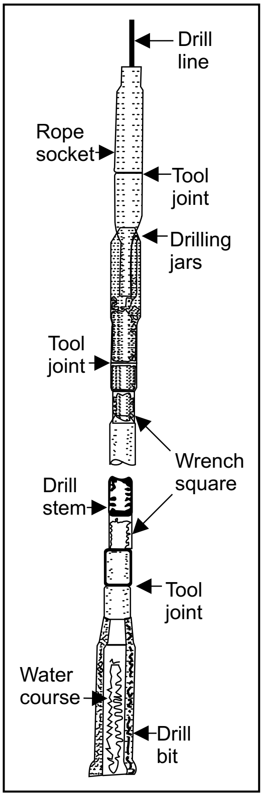

Fig. 5.13 Drill tool assembly for cable tool percussion drilling

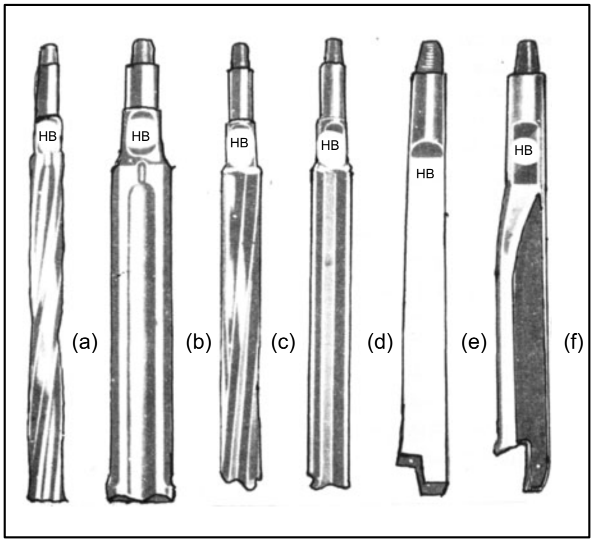

Fig. 5.14 Different types of drill bits used with percussion rigs: (a) Deep-fluted twist drill bit (for hard formations), (b) Flat-fluted drill bit (for soft rock strata), (c) Twist star drill bit (specifically suited when the formation is at an angle), (d) Straight star drill bit (for heavy duty jobs and straightening crooked holes), (e) and (f) Enlarging drill bits. *Courtesy:* Hardwood Bagshaw Engg. Ltd.

A drill bit has four important functions, viz. penetrating, crushing, reaming, and mixing. The character of the formation to be drilled determines which of the four functions is the most important. For example, while drilling in hard limestone formations, the most important function is penetration. If the rock, has a high silica content, it will be abrasive and in this case, the function of reaming must also be considered. Hard, solid limestone with no vertical seams or open fissures to deflect the drill hole, is drilled with a bit with a sharp angle of penetration. The contour of the penetrating edge is slightly concave and if the formation is not abrasive, a wide angle of clearance is used. If fissures are encountered, the penetrating angle is greatly increased, making the bit blunt.

Drilling in soft limestone requires special attention to the crushing function. If the limestone contains a noticeable amount of clay, some attention must be given to mixing. Soft limestone with open reams, fissures, and hard spots requires a drill bit with a maximum reaming edge, a liberal angle of clearance, and an ample crushing-face area.

Quartzite and granite are usually hard and abrasive. Therefore, the important functions of the drill bit are to penetrate and to ream, and no attention need be given to crushing and mixing. Granite, quartzite, and trap-rock with vertical seams and fissures require a drill bit with a wide angle of penetration which forms a thick, heavy, cutting edge to withstand the impact of heavy tools. The wearing surface should be as straight as possible, allowing little or no angle clearance. The cross-section of the bit should be large, in order to guide the tools in the hole and prevent off-setting when fissures are encountered.

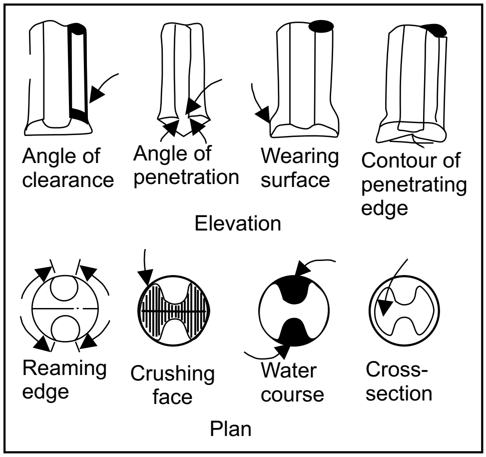

Fig. 5.15 Details of the cutting edge of drill bits used in cable tool drilling *Adapted from* U.S. Dept. of Army and Air Force Tech. Manual (Anon, 1957)

While drilling in soft shale, clay or soft limestone, special attention is required for mixing. In many cases, it is necessary to retard penetration in order to secure the maximum mixing results. These formations, require a drill bit with little, if any, penetrating angle. The greatest possible angle of clearance is used, as the cross-section or body size of the bit is small. A large area of crushing face is given to the bit for the purpose of retarding penetration and at the same time, packing the material in the bottom of the hole to prevent the tools from diving and sticking.

The size of the drill bit is selected on the basis of the diameter of the hole to be drilled. However, the length of the bit may be varied, according to the weight required to provide adequate capacity to the drilling machine. Figure 5.14 shows the common types of percussion drill bits and their adaptability. Common types of travel blocks, clamps and lifting devices used in percussion drilling are shown in Fig. 5.16.

Bailer

A bailer or sand pump is used to remove the drilled cuttings from time to time. A bailer consists of a section of pipe, generally 2-5 m long, with a valve at the bottom and a hook at the top for attaching the cable. It is provided with a cutter shoe at the bottom. The diameter of the bailer is determined by the size of the hole being drilled, sufficient clearance being allowed so that the bailer will fall free. Bailers are generally equipped with flap, or dart valves (Fig. 5.17). The flap valve cannot be opened after the bailer is filled, and it has to be emptied from the top by tipping the bailer. The design, however, enables the bailer to clean-out closer to the hole bottom. The bailer with a dart valve is emptied by striking the dart attached to the valve on something solid, which forces the valve open. It is used for rapid bailing of the cuttings, which mix with water during drilling and are kept in suspension. A sand pump is similar to a bailer, except that it is equipped with a piston for the purpose of drawing the drilled cuttings from a well. It is used for removal of heavy cuttings and is more effective than a flap-valve bailer.

The up-and-down drilling action is imparted to the drilling tools and the drill line by the walking beam, which is pivoted at one end. Its outer end, which carries a sheave for the drill line, is made to oscillate by a single or double pitman connected to a crank gear. Both the vertical stroke and the speed of action can be adjusted. The crank gear is driven by a pinion mounted on a friction clutch. The clutch, the friction drive for the sand line and the drive pinion for the drill-line reel are all mounted on the same drive shaft assembly.

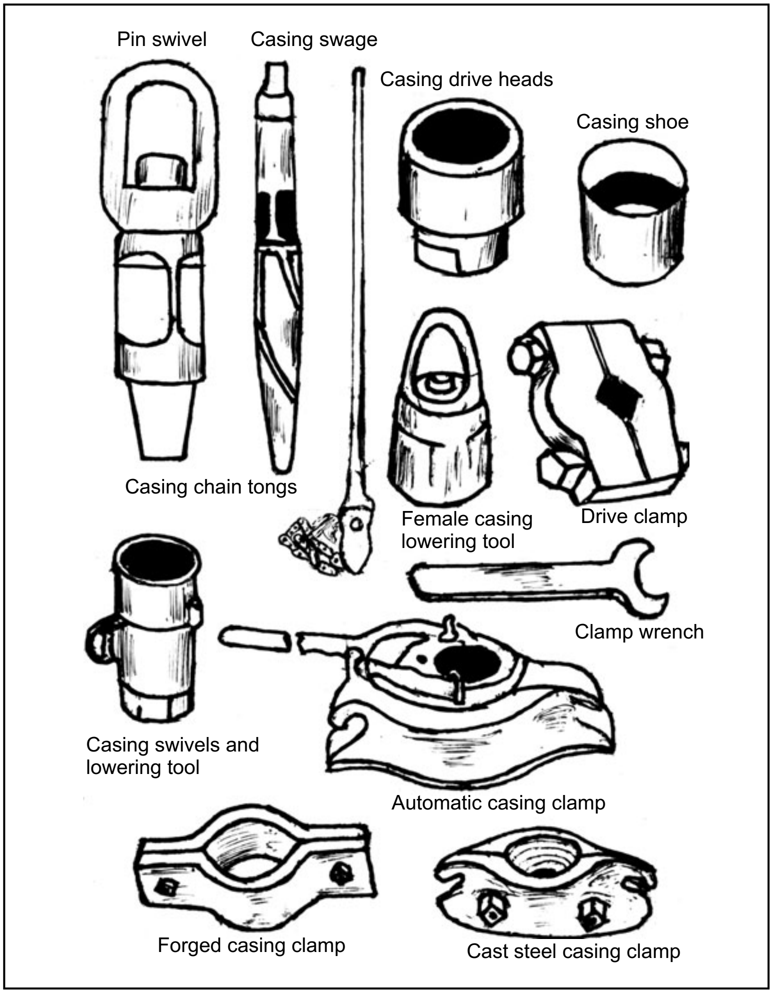

Fig. 5.16 Common types of travel blocks, clamps and lifting devices used in percussion drilling
Courtesy: Hardwood Bagshaw Engg. Ltd.

Standard Cable Tool Drilling Procedure

Once the well location is fixed, the rig is placed over it and levelled properly. After the rig has been erected and its alignment checked, drilling is started by raising and lowering the string of tools at the end of the drilling cable. The cable is operated by the spudding mechanism of the rig. During drilling, the tools make 40–60 strokes per minute, ranging from 40–100 cm in length. The drilling line is rotated so that the bit will form a round hole. As already stated, water is added to the hole, till the water table is reached, to form a paste with the cuttings, thereby reducing friction on the falling bit.

The drill cuttings are bailed out at regular intervals as the hole is drilled. The depth of the hole that can be made at each run of the tool will vary according to the strata encountered. Although conditions differ greatly and no rule can be set, a 1.25–1.5 m hole with each run of tools may be a fair average. After each run, the tools are pulled from the hole and swung aside while the bailer is used. The above procedure is repeated, till the required depth of hole is reached.

Casing of Drilled Holes

The bore hole in the percussion method is lined with steel casing pipes, also called boring pipes. These pipes are removed after the well is drilled to the full depth, well pipes (plain pipes and strainers) are lowered and gravel packing is completed. An open hole without casing may stand in a rocky formation. However, inserting casing pipes in porous formations is an essential feature of percussion drilling. While drilling with percussion rigs, the casing pipe may be installed in the hole by any of the following methods:

1. It may be made to sink by its own weight.
2. It may be loaded with extra weight to facilitate sinking (Fig. 5.7).
3. Downward pull may be applied by hydraulic or jack screw (Fig. 5.8).
4. The pipe may be driven in by hammering (Figs. 5.18 and 5.19).

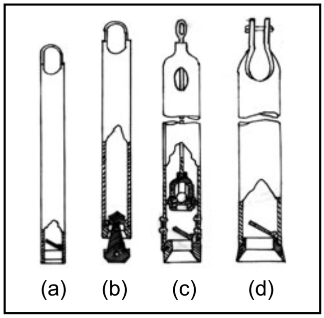

Fig. 5.17 Exposed view of bailers with different types of valves and a mud scow: (a) Flapper; (b) Dart valve; (c) Bayonet valve; (d) Mud scow

Selecting Proper Size of Casing Pipe

The selection of the size of the casing pipe depends on the formation in which the well is to be drilled. If the geologic features of the formation are unknown, the largest casing pipe available is used because of the uncertainties in driving the pipe. The following are the possible uncertainties:

1. Possibility of striking thin beds of hard limestone through which the pipe cannot be driven.
2. Wide differences in frictional resistance to the drive pipe in different types of unconsolidated materials, which make it difficult to predict the depth to which any single string of pipe can be driven.

Either of the possibilities mentioned above, may necessitate a reduction in hole size at any time. For this reason, where sub-surface conditions are unknown, the hole is started at least one size larger than necessary for completion.

Seating the Casing Pipe in Rocky Formations

Seating the casing in percussion drilled wells usually consists of driving the well casing into the hard rock for a few centimetres or metres. The casing shoe is driven far enough into the rock to make a perfect seat, shutting out all surface water, silt and sand that might enter the well. Often it is necessary to drive the pipe ahead of the tools, until the rock is struck.

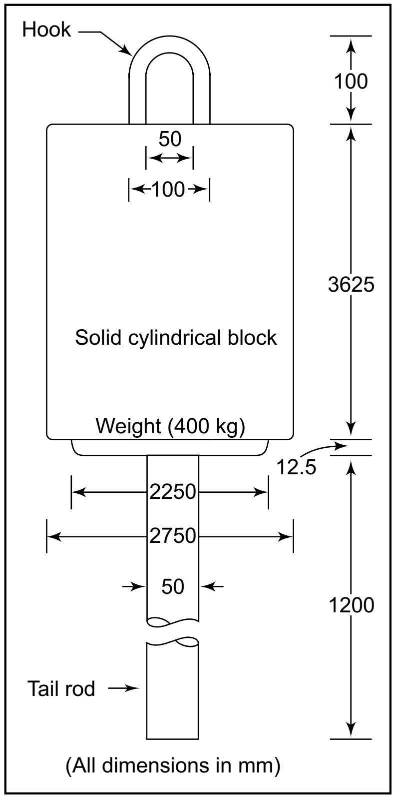

Fig. 5.18 Drop-hammer for driving in the casing pipe in cable tool drilling

Drilling Motions

Drilling motions must be kept in step with the gravity fall of the tools, for good operation. Variable factors interfere with the gravity fall and the driller must adjust the motion and speed of the machine with the cycle of tool travel. An effective drilling action is obtained when the engine speed is synchronized with the fall of tools and stretch of cable, to maintain the proper feed of the bit.

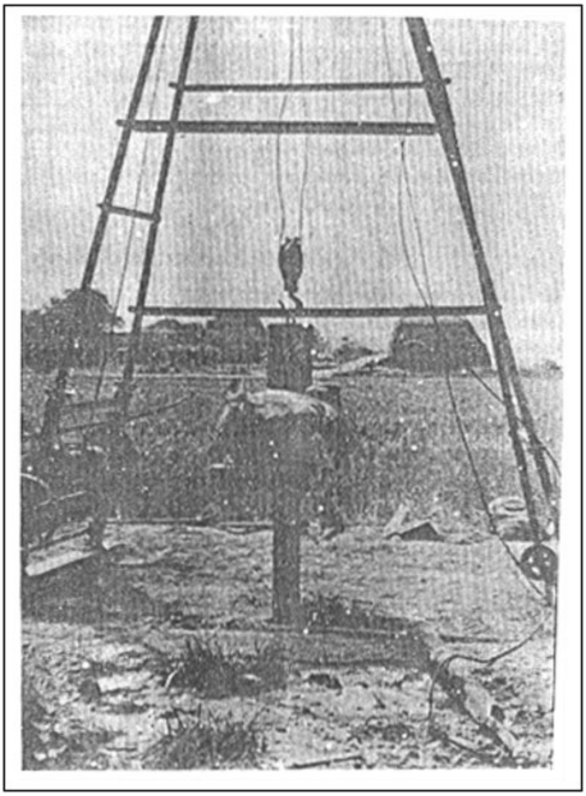

Fig. 5.19 Weighted drop hammer and sand bags used to drive in the outer casing pipe in cable tool drilling

Strata Sampling

The excavated material which is brought to the surface by the bailer will indicate what type of stratum is being passed through at the bottom of the bore. Samples of the material are kept in a box, in different compartments, showing the type of material at different depths (Fig. 5.20). A strata chart is prepared to design the tube well assembly. Mechanical analysis of the aquifer sample is carried out to design the well screen and the gravel pack. The assembly of component parts of the well, viz., the bail plug, well screen and blank pipe are designed and marked in the chart. The assembly is prepared and placed in a line on the ground surface, in the order of their lowering in the bore.

Difficulties During Percussion Drilling

While operating drilling rigs, particularly mechanically operated equipment, several difficulties are encountered. While all such difficulties and their remedies can be understood after some experience in field operations, some of them are described below:

Fig. 5.20 Strata sampling box for well log. The samples obtained from different depths during drilling are collected in different compartments of the sampling box. Note the number tags indicating the ranges in depth from which the samples have been obtained.

Jammed Pipes

The boring pipes used for boring tube wells should normally be flush-jointed. In case collar-type joints are used, there is sometimes jamming of pipes. This occurs due to the collar obstructing the bore. The pipes may also be made immovable by mud, sand or other gritty substances settling around them. In such a situation, instead of applying a large force, which may not prove helpful, the pipes should be worked up and down, as far as possible. This maybe done repeatedly, so that the collar loosens the material and passes the point where it is obstructing the bore. At some places, dynamite is used to give jerks to the pipe and loosen it from the earth surrounding it. This operation, however, is to be carried out with great care.

Sand Blowing (Quicksand) During Boring

At some places, if a sand layer is confined between two strata, sand may rush into the boring tubes, making the boring operation difficult. Quicksand comes into the drill hole and must be bailed out in large quantities, before the casing can be driven farther down and drilling continued. In such a situation, the progress of boring becomes very slow and the drilling tools may get jammed in the sand. To overcome this difficulty, the clamp holding the casing pipe could be kept loose, in order to allow the sinking of the casing pipe as and when the sand is cleared. The casing pipe could also be kept full of water, the pressure of which may prevent sand from rushing in.

Wells Sunk Out of Plumb

If vertical turbine pumps are to be installed in a tube well, it is necessary that the drilling of the bore should be almost perfectly vertical. To set right a non-vertical boring pipe, the soil around it in the direction it has to be pulled, is loosened and the boring pipe set in alignment with jacks. Sometimes, additional boring has to be done by the side of the first bore to push the pipe into a vertical position. When the pipe has been forced into the correct position, the space left has to be filled with gravel and earth and rammed to keep the pipe in position. Making the bore truly vertical is not essential if ordinary centrifugal pumps are to be installed for pumping.

5.3.3 Dressing of Drill Bits

The outer wearing surfaces of drill bits become worn due to continued use. This is because of their rubbing on the inside walls of the pipe and the open hole below the pipe. Abrasive underground formations give rise to grater wear than soft formations. Several methods are used for dressing of bits, based on the availability of equipments and individual preference (Fig. 5.21). Irrespective of the method adopted, the drill bits require particular care in heating for forging and in heating for hardening (tempering). Before the bit is put into a hot forge, some preliminary heating (about 375ºC) must be given to the bit, otherwise there will be a danger of its cracking.

In case an oil or gas-fired furnace is used, the bit end should be heated first and then slowly pushed progressively farther into the furnace until it becomes hot enough to sizzle when sprinkled with water. After pre-heating, the bit is heated to the required temperature of about 1,100ºC in a forge. Uniform heating of top, bottom and sides of the bit should be ensured. However, frequent turning of the bit should be avoided.

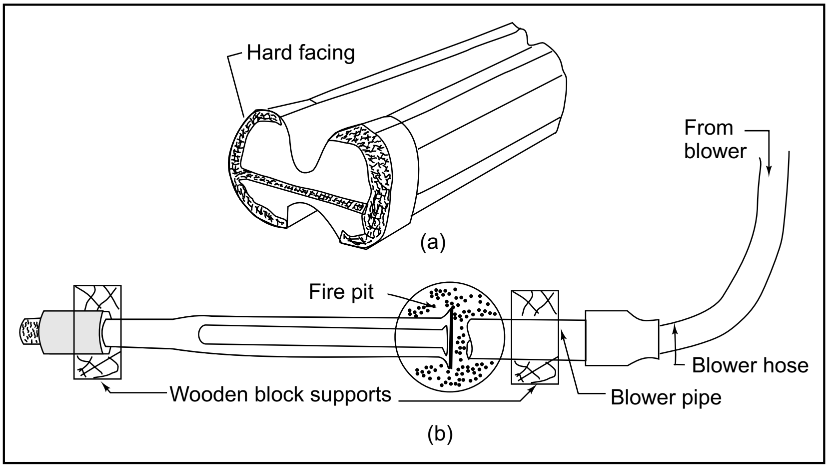

Fig. 5.21 Dressing of drill bit: (a) Bit areas to be hard faced, (b) Bit position while heating

When the bit has been heated to forging temperature, it is transferred, as quickly as possible, from the fire to the anvil block for forging. Small size bits can be handled manually while for large size bits, lifting blocks can be used. The bit is struck alternatively against its centre to bring it to gauge; forming the proper contours of the penetrating edge. After striking the bit with one or two blows, subsequent blows are delivered progressively towards the outer edges, along the centre line. This is followed by two or three final blows given at the face, a little higher up from the centre line, and two or three pulling blows at the corners, which result in drawing the corners to gauge.

After working on one side of the bit, it is turned over and the same treatment is given on its opposite face. At this stage, the bit is usually larger than the required size. A few hammer blows are delivered on each face to bring the face edges to correct gauge. The bit is then turned on its side and held in position by one man while the tool dresser forms the angle of clearance and wearing surfaces, first on one side and then on the other to bring the final circumference to gauge.

After dressing the bit to its proper size and shape, it is set aside to cool before reheating for hardening. Before reheating, the furnace must be brought back to the temperature at which the bit is demagnetised. The bit is heated evenly with frequent turning. It gets ready for hardening when the temperature rises to the point at which it loses is magnetism. The colour of the heated end becomes dark cherry red. It is then withdrawn from fire and tested with a magnet. The bit is then removed from the fire to a slack tub. Sufficient water is poured to reach as high as the corner of the bit. The bit is left in water until the red colour has almost disappeared.

Adaptability of Cable Tool Drilling Method

Cable tool percussion drilling can be used successfully in all types of formations. It is, however, better suited than the rotary method for drilling in consolidated formations containing large rocks and boulders. The main disadvantages of the method are its slow rate of drilling and the need to case the hole as drilling progresses. However, the following advantages account for its widespread use:

1. Reasonably accurate sampling of formation materials
2. Water quality and yield of different water-bearing strata can be estimated during drilling

3. Much less water is needed for drilling than in the hydraulic rotary and jetting methods (this can be an important consideration in arid regions)
4. Any encounter with water-bearing formations is readily noticed as water seeps into the hole
5. The well driller need not be as skilled as his counterpart in rotary drilling
6. Suitability for drilling in hard formations.

5.4 HYDRAULIC ROTARY DRILLING

Hydraulic rotary drilling consists of cutting a bore hole by means of a rotating drill bit, and removing the cuttings by the continuous circulation of a drilling fluid. The drill bit is attached to the lower end of a string of drill pipes. The two important items in the rotary drilling method are the drill bit and the drilling fluid. Both are indispensable in cutting and maintaining the bore hole. All the components that make up the rotary drilling machine are designed to serve two functions simultaneously—operation of the bit and continuous circulation of the drilling fluid. Hydraulic rotary drilling is of two types, namely, direct circulation drilling and reverse circulation drilling.

5.4.1 Principles of Direct Circulation Hydraulic Rotary Drilling

The direct circulation drilling process involves boring a hole by using a rotating bit to which a downward force is applied. The bit is supported and rotated by a stabilizer to which the drilling pipes are attached. The drilling fluid, also called drilling mud, is pumped down through the drill pipe. The fluid passes out through nozzles in the drill bit. It then flows upward in the annular space around the drill pipe, to the ground surface, with the cuttings carried in suspension. At the surface, the fluid is channelled into a settling pit and then into a storage pit. It is again picked up by the pump after dropping the bulk of its load of cuttings. A schematic view showing the basic principles of direct circulation rotary drilling is given in Fig. 5.22.

5.4.2 Direct Rotary Drilling Rig

The primary equipment for direct rotary drilling is the direct rotary rig, which can be bolted to skids, mounted on trucks (Fig. 5.23), or mounted on trailers. It consists of a mud circulating system and rotating and hoisting mechanisms.

The circulating system consists of a mud pump, piping and valves, hoses and flow lines. The normal circulating fluid is mud, which may be made up of many different substances and water. It is necessary that the fluid is able to lift the cuttings from the hole and keep the wall of the drill hole intact to prevent sticking of drilling pipes.

The mechanism that rotates the drill pipe consists of a kelly, drive bushing, pins, quill and rotary table. The kelly is a thick-walled special steel tube which generally has three flutes milled lengthwise, all along the outside diameter. The flutes act as a means of producing rotary motion and leaving the kelly free to move up and down. The drive bushing has a matching set of flutes on the inside. Three floating, hardened pins are used to transfer power from the drive bushing to the kelly.

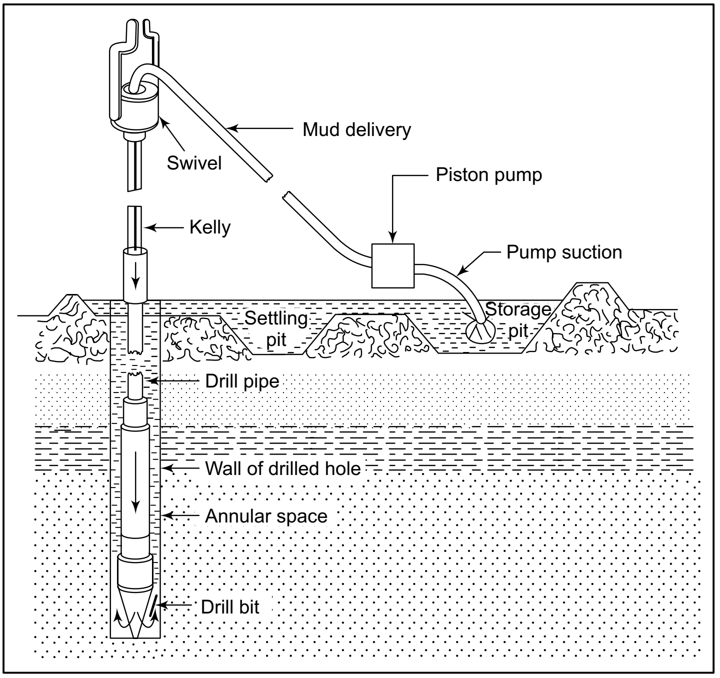

Fig. 5.22 Schematic sketch illustrating the basic principles of direct rotary drilling

Fig. 5.23 A medium duty direct rotary rig
Source: Brochure on Drilling Equipment. Government of India, Ministry of Agriculture, Community Development, and Cooperation Department of Agriculture

Hoisting Mechanism

The hoisting mechanism consists of a main hoist, sand-reel hoist and cat-head. The main hoist consists of a drum, friction-type clutch and brake, all of which are protected by a sheet-metal housing. The drum is constructed of steel, with a spool capable of winding about 500 m of 10 mm diameter wire rope. The reel is driven by the power transmission unit. It is used to handle the short strings of drill pipe and well screens, and for other light lifting. The cat-head is constructed of cast iron and keyed to the main hoist-drive shaft operated by a reduction gear drive. It operates independent of the main hoist and the sand-reel hoist. It is useful in making and breaking drill-rod connections and driving or jarring the pipe.

Drill Head

The drill head consists of a rotating mechanism hoisting drum, sand reel, hydraulic cylinders for applying added weight to the drill bit, and a hydraulic transfer cylinder for moving the drill head in to-and-fro positions. All these items, with their respective controls and driving mechanisms, are mounted on cast-steel fabricated frames. The gears run in oil-tight cases, cast integral with the frame. Other moving parts are also well protected.

Transmission

Power is transmitted through a clutch and a selected speed transmission gear box. A square steel shaft with universal hook joint connects the drill head input shaft to the transmission box. The input shaft runs on tapered roller bearings. On the shaft, between the two tapered roller bearings, a spiral bevel pinion is provided, which drives the cat-head shaft. One end of the input shaft is splined and carries the movable part of the jaw clutch that connects the power to a rotating bevel gear. The jaw clutch is engaged or disengaged by a lever provided outside the frame.

The spiral bevel pinion for rotating the kelly is firmly secured in a housing, and runs on a double-row tapered roller bearing at one end and a plain roller bearing at the other, in order to counteract the thrust. The bevel gear, known as crown gear, driven by this pinion, is riveted to the flange of the drive quill. The drive quill is vertical and supported in the main-frame housing by tapered roller bearings mounted at the retainer plates which are bolted to the housing. Oil seals are used to prevent leakage of oil.

The hoisting drum and the sand reel are driven by means of roller chains from the cat-head shaft, which extends out at right angles to the input shaft. The cat-head shaft is driven by a spiral bevel gear running in mesh with the spiral bevel pinion on the input shaft. The cat-head is mounted on this shaft, outside the drill head frame. The hoisting drum is mounted at the top near the centre of the drill, while the sand reel is mounted slightly lower and at the back of the hoisting drum. Both drums are equipped with friction multi-disc clutches and mechanical brakes. The clutch control and brake handles are provided beside the operator.

Mud Pump

The direct rotary drilling rig is equipped with a duplex reciprocating type pump (Fig. 5.24). The pump capacity depends on the job requirement. The mud pump is the heart of the mud circulating system. The pump forces, the drilling fluid from the main pit through the foot valve and pressure hose, through the swivel joint, kelly, drill, pipe and out through holes in the drill bit. The return flow is through the annular space to the settling pit. The pump is of the piston type, with removable hardened steel cylinder liners. The piston has a one-piece alloy-steel body containing replaceable double-lipped cups of abrasion-resistant rubber. The liners, pistons and valves are the vital parts of the pump and are subjected to the greatest wear and tear from abrasive materials in the circulating fluid.

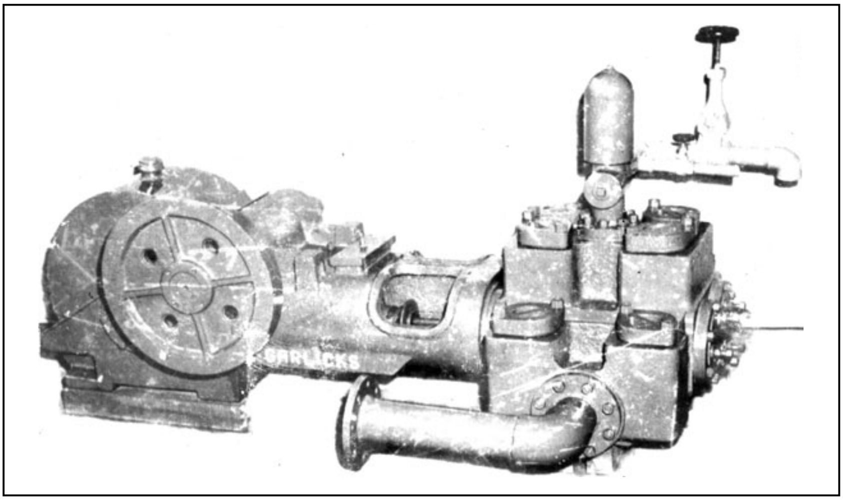

Fig. 5.24 A horizontal heavy-duty duplex double-acting reciprocating type mud pump used in direct rotary drilling. The pump has a capacity of about 750 lit/min and a maximum pressure of 70 kg/cm2
Courtesy: Garlick and Co. Pvt. Ltd., Mumbai (Anon, 1973)

Mast

The mast is fabricated from solid, cold-drawn, seamless steel tubings, and reinforced for structural strength. The mast is raised or lowered by two double-acting hydraulic cylinders, with safety checks attached to prevent accidental dropping. The legs of the mast are provided with screw jacks and clamping arrangements. The mast is equipped with clamps for holding the kelly, and a lighting arrangement in order to facilitate night operation of the drill.

Manually Operated Rotary Drilling Rig

Manually operated rotary rigs enable drilling of shallow tube wells at faster rates in alluvial formations, as compared to their percussion-type counterparts. The equipment consists of a single-acting double-cylinder manually operated vertical pump which provides the necessary fluid pressure at the bottom of the hole for flushing out the cuttings. The fluid is transmitted from the pump to the bottom of the hole through a rubber hose, water swivel, drill pipe and cutting bit (Fig. 5.25). The drill string is supported from a travelling block hung from a tripod. While the vertical feed is controlled through a manually operated winch, the rotary motion is imparted by rotating the drill pipes with the help of a pair of chain tongs. The cuttings are brought to the surface by the mud fluid. The equipment is usually used for drilling small wells of 5 to 6 cm diameter and depths upto 50-60 m. The method is used in some parts of Orissa and other regions in the alluvial plains of the east coast, mainly for constructing wells for domestic water supply.

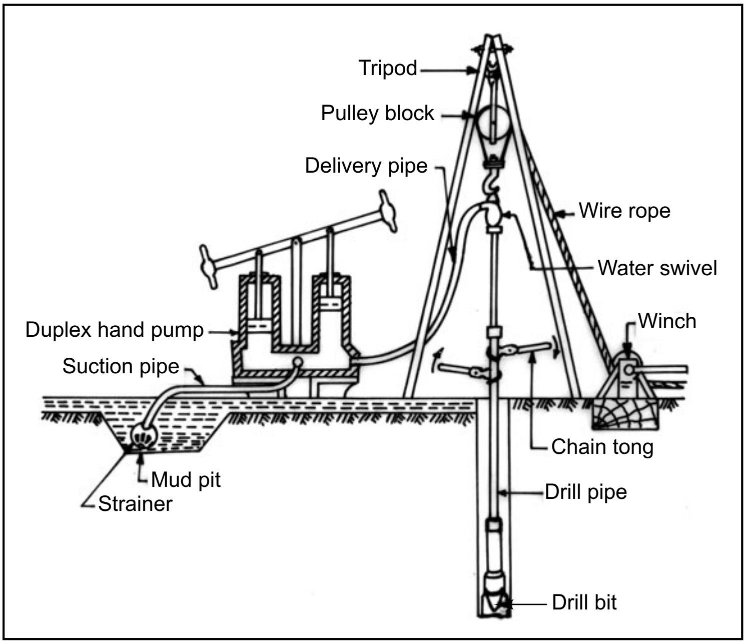

Fig. 5.25 Schemetic sketch of a manually operated rotary drilling rig showing the component parts, including the duplex hand pump and winch

Drill String

The drill string (Fig. 5.26) for rotary drilling consists of a drill bit, drill stem and swivel.

Drill Bits

The efficiency of drilling rests largely on the bit. Drill bits may be divided into two broad classes: (a) drag bit, and (b) rolling-cutter type bits, also called rock bits (Fig. 5.27), The drag bits have a shearing and scraping action. They are adapted to drilling in soft and unconsolidated formations. They have short blades or wings, which are forged and dressed to form thin cutting edges. The wearing surfaces are hard-faced and dressed with hardened inserts set in the corners. The body of the bit is hollow, with holes positioned for directing the drill mud to keep the blades clean and cool and at the same time assist penetration by a jetting action against the bottom of the hole. The drag bit may be a two-way bit, called the fish-tail bit because of its resemblance to a fish tail. It may also be a three-way or six-way bit. The two-way bit with two blades is adapted specially to loose sands and clays. The three-way bit is much like the fish tail in design, but has three cutting blades instead of two, which make the drilling action smoother in shattered or irregular formations. It also makes a better hole in semi-consolidated formations and has a lesser tendency for deflection. In soft formations, it cuts a little slower than the fish tail. The six-way bit, also called pilot bit, has six cutting edges, each with a hole for circulating the drill fluid. Three of these cutting blades cut a hole of about half the diameter cut by the other three. This bit is more suited to shattered formations and cemented sands than either the fish tail or three-way bit. It will cut somewhat harder formations, and with less irregular strain on the drill rods.

Roller type bits are specially adapted to drilling into hard formations. They exert a crushing and chipping action which makes it possible to cut hard formations effectively. The teeth of a rock bit are milled on the surface of cones or rollers, which revolve as the bit is turned. A jet of circulating fluid is directed from the inside of the bit to the top of each cone or roller. Rock bits cannot be successfully readdressed. Basically, there are two major types of roller bits, the cone bit and the cross-roller bit (Fig. 5.27). Bit with cones or rollers having long teeth with wide spacing are best suited for soft rocks.

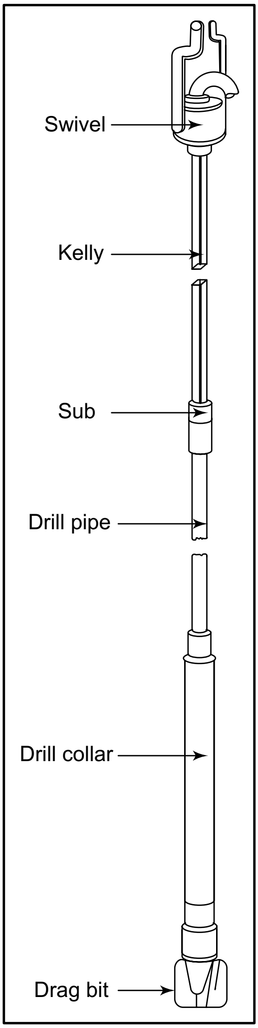

Fig. 5.26 Drill tool assembly for rotary drill
Adapted from: Garlick & Co. Pvt. Ltd, Mumbai (Anon,1973)

Harder formations require bits with shorter teeth which are more closely spaced. A cone-type bit has three cones, a forged-steel body, and a cone axle or pin, which form a part of the body. The cones have roller bearings fitted at the time of assembly. The 3-cone construction provides smooth operation. Bits with different shapes of cutting surface and varying designs of teeth are available to suit different formations. All cutting surfaces are flushed by the circulating fluid. The tri-cone bit is more generally used, due to its structural strength and balanced cutting action.

Cross-roller rock bits constitute a broad class of bits that have their main cutting elements disposed on a right-angle cross. The cross-roller bit usually consists of four cutters arranged so that all four cut the bottom of the hole, but only two cut the hole to gauge. As in cone bits, the teeth of this type of bit vary with the formation to be cut. The cross-roller bit is generally used in formations where there is a tendency for the bits to become crooked. It is also used to straighten crooked holes.

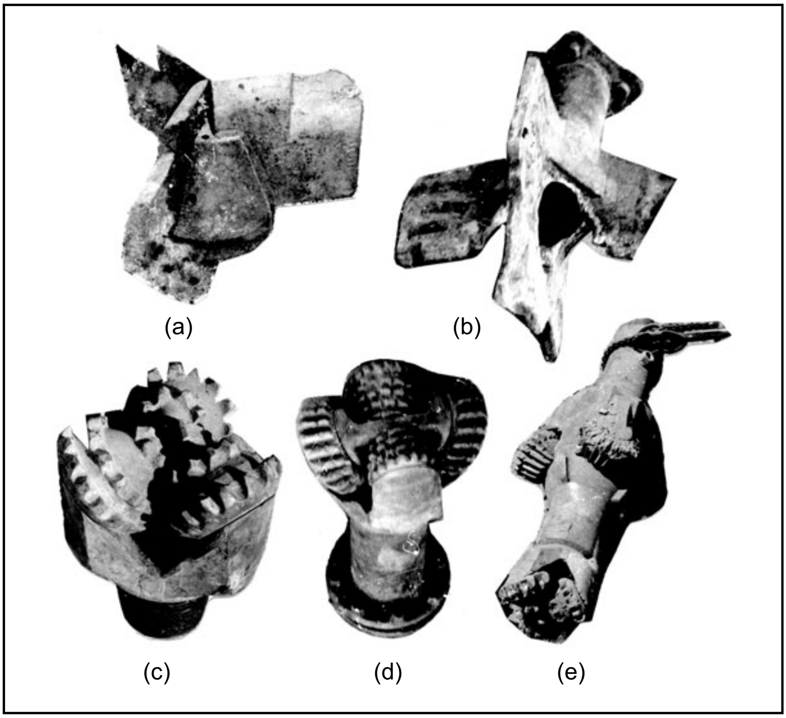

Fig. 5.27 Drill bits for direct rotary drills: (a) Three-way drag bit, (b) Six-way drag bit (c) 3-cone roller bit, (d) Cross-roller bit, (e) Reamer bit equipped with rollers for pilot hole and reaming

Dressing of Drill Bits

Amongst the rotary drill bits, roller bits are not usually renewable. However, all types of drag bits can be sharpened or redressed by building up worn cutters with steel and hard-surfacing metal, using an oxy-acetylene torch to fuse the new metal to the worn edges (Fig. 5.28). The following procedure is used in redressing the bits:

1. Grind down the cutting edges of the drill bit until the old metal surfacing from previous dressings has been removed.
2. Using high strength steel welding rod, build up the surface to slightly below the desired finished height.
3. Re-size the outer diameter of the bit.
4. Using hard-surfacing rod, build up the surface, especially along the edges, to slightly above the desired finished heights.

5. Shape the cutting edges by grinding.
6. Recess the tips of cutting surfaces and set in tungsten carbide inserts, positioning them as in Fig. 5.29.
7. Grind the bit to size and shape the cutting surfaces. A redressed bit is shown in Fig. 5.29.

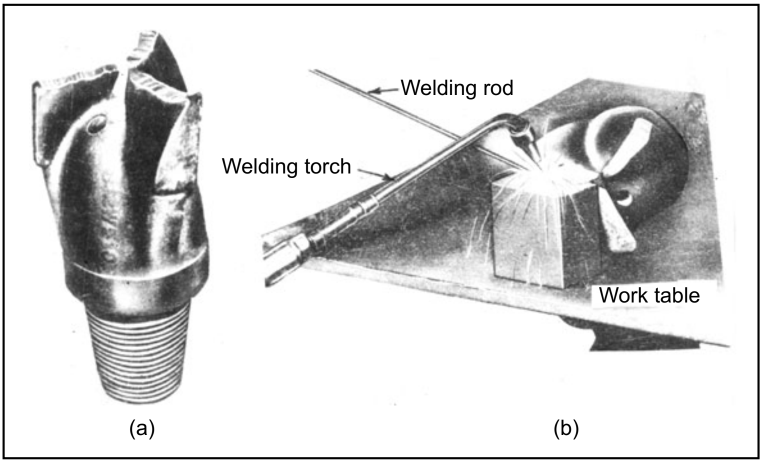

Fig. 5.28 Dressing of a worn drag bit: (a) Worn drag bit, (b) Building up the surface of the cutting edge with a high-strength steel welding rod, using oxy-acetylene torch to fuse the new metal to the worn edges
Adapted from: U.S. Army and Air Force Tech. Manual (Anon, 1957)

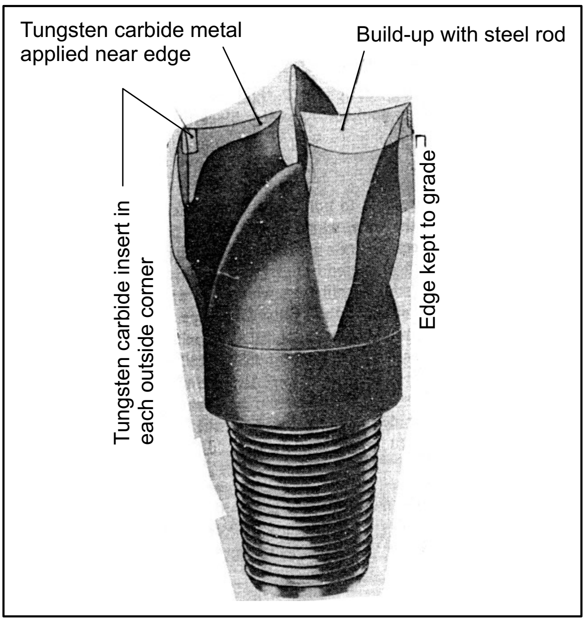

Fig. 5.29 A freshly dressed 3-way drag bit
Adapted from: U.S. Army and Air Force Tech. Manual (Anon, 1957)

Drill Stem

The drill stem is a hollow rotating shaft which operates the bit at the lower end. It forms the link between the bit and the surface. It usually consists of 3 parts, (a) one or more drill collars just above the bit, (b) one or more lengths of drill pipe, and (c) the kelly.

Drill Pipe

The drill pipe is a seamless tubing, usually of 6 m length, with a tool-joint pin on one end and a tool-joint box on the other. The outside diameter of the drill pipes used for water well drilling usually ranges from 6 to 12 cm. In water well work, it is important to use a drill pipe of as large a size as possible because the drilling demands a relatively higher rate of circulation of the drilling fluid. A drill pipe with a large internal diameter keeps down friction losses in the pipe and reduces the power requirement of the pump.

Kelly

The kelly is the upper-most section of the drill stem. It passes through and engages the kelly drive bushing in the rotary table by means of driving pins. While rotating, it slips down through the drive bushing as the bore hole is made. The kelly is usually square or hexagonal in section. The lower end is connected to the first joint of the drill pipe through a sub, which is a short tubular connection which saves the threads on the kelly from wear due to frequent screwing and unscrewing. It is replaced when worn.

Swivel

The upper end of the kelly connects to the water swivel (Fig. 5.26). The swivel is so built that the weight of the entire drill string is supported on freely moving bearings. This permits the drill stem and the bit to rotate with the driving mechanism during the drilling operation, while the upper part of the swivel remains stationary. The swivel also provides the mud-hose connection. This permits free passage of the drilling fluid as drilling proceeds. The drilling fluid passes through the swivel to the drill pipe and the bit. The swivel is hooked to a pulley block assembly called the travelling block (Fig. 5.16).

Spiders and Slips

Spiders and slips are used to hold the string of the drill pipe when it is disconnected from the kelly, while a joint of drill pipe is being removed or added. The spider consists of a spider bowl and a split ring. The spider bowl is a sleeve with a tapered bore large enough to accommodate the slips and the pipe to be held. A split ring, which is a tapered bushing, fits in the spider bowl. It is used when the drill rods or pipe are to be held.

Slips (Fig. 5.30) are curved wedges, provided with handles and fastened together in sets of pairs. They are heat-treated to ensure long life and a good grip on the pipe. Each set of slips is made to hold a pipe of certain diameter. The inside face of the slip has teeth which grip the outside of the pipe. The outside face is tapered to fit the taper in the spider bowl or split bushing. When the slips are set around the pipe, the teeth grip it and the weight pulls the slips down in the tapered bore of the spider. This wedges the slips against the pipe, holding it firmly. The teeth of the slips should be cleaned regularly so that they grip the pipe well.

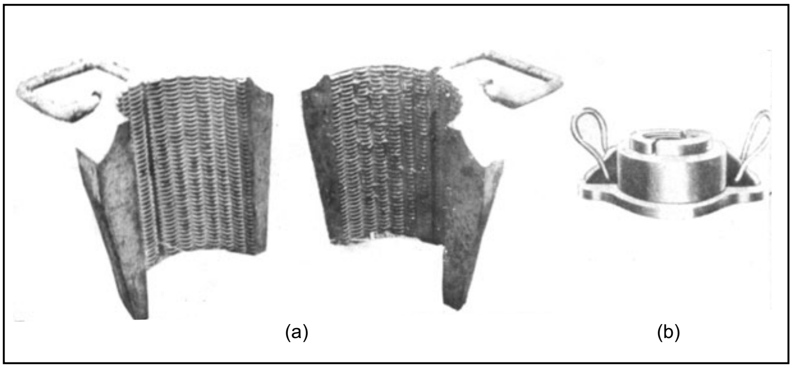

Fig. 5.30 Casing ring and slips: (a) A pair of slips, (b) Casing ring and slips used to suspend the well casing at the ground surface. They are also used when pulling the pipe from the hole by jacks placed under each of the casing rings.

5.4.3 Operation of Direct Rotary Drills

Generally, a crew of three men, consisting of the driller and two helpers, is required to operate the rig. Additional men are required for hauling water, moving the equipment, and placing the rig in position. The driller is in charge of all the operations and is responsible for the care and maintenance of the equipment. The helpers keep the settling pit clean, maintain an adequate water supply, keep fuel and water in the engine and lubricate the equipment. When running the drill pipe in or out of the hole, one helper works on the ground and helps the driller. He sets the slips, screws the hoisting plug in and out, and helps to handle the pipe. The other helper works on the mast platform. He screws or unscrews the hoisting plug and helps guide each section of the pipe while it is suspended in the derrick.

Setting the Drilling Rig

After a site is selected and levelled, the drill is moved into position. The main pit for the storage of water and pits for settling of cuttings are excavated. The rig is jacked up with screw jacks and levelled. Suitable wooden sleepers are provided below the screw jacks. The earth below the wooden sleepers should be well compacted so that during the process of drilling the alignment of the rig is not disturbed. The level of the drill head is checked, both longitudinally and transversely, and minor adjustments are made to ensure precision levelling. After jacking up the rig, the derrick is erected carefully. After the mast has been fully erected, it should be locked in position with the help of two latches. The level of the drill head is checked again and the derrick checked for its plumbness. Minor adjustments are made, if necessary. During the drilling operation, the alignment of the rig and the level of the drilling head are periodically checked and corrected, if necessary to ensure a vertical and true hole. Any negligence on the part of the operator may result in an out-of-plumb and crooked hole.

Drilling Fluid

Drilling fluid (often called “mud”) is used in the drilling operation to cool and clean the drill bit, lift the cuttings from the bottom of the bore hole and carry them to a settling pit, prevent recirculation of cuttings, create a thin film of small particles on the borehole wall to prevent caving and seal the borehole wall to reduce fluid loss to the formation (lost circulation), lubricate mud pump, bit and drill pipe, and prevent formation water from diluting the mud.

Drilling fluids, may be water based, air based, or oil based. Water based drilling fluids include fresh water, water with clay additives, water with polymeric additives and water with a mixture of clay and polymeric additives. Commonly used drilling fluids fall into two categories: bentonite based and biodegradable. Biodegradable drilling fluids (such as German brand Antisol(R), U.S. brand Revert(R)) are thought to cause less clogging than non-degradable fluids such as bentonite (Segalen et al, 2005). They prevents caving, drops cuttings in the mud pit better than bentonite mixtures. Biological breakdown causes them to change to a fluid as thin as water after several days, which can be thoroughly flushed from the well and the well can be developed as easily as if only clear water had been used in drilling. Dispersants, wetting agents, weighing materials, thinners and lubricants are added to modify properties to meet changing hole conditions.

Mud is probably the most commonly used drilling fluid. It is generally a mixture of commercial clay, commonly known as bentonite clay (sodium montmorillonite) and water. The water used should be reasonably free from dissolved salts. Some salts soluble in water tend to alter the clay-suspension properties of the mud. Salt water or water with a high chloride content will tend to flocculate (curdle) the clay particles and destroy the colloidal properties of the mud, which are essential in wall building and sealing of permeable formations.

When bentonite is added to water several changes in physical properties take place. Some of the more important are increases in density and viscosity. These can be easily measured and related to performance and are described below.

Density

Drilling fluid density is measured by a simple balance beam or mud balance and is usually expressed in g/cc. As density is increased, the buoyant effect increases carrying capacity for cuttings but decreases settling rate in the mud pit. Increased density increases bore hole pressure and ability to prevent caving and flow into the hole conversely, it increases the tendency to flow out of the hole and into the formation, and therefore, may result in increased loss of circulation. The generally, recommended maximum density is 1 g/cc.

Viscosity

Drilling fluid viscosity is primarily a measure of its ability to carry cuttings up the hole, drop them in the mud pit, and to form a gel. It is changed by varying amount of bentonite and water or by adding polymers to thicken or phosphates to thin. In the field, apparent or funnel viscosity is obtained by measuring the time it takes a measured amount of mud to flow through a standard Marsh Funnel. A good drilling mud has a funnel viscosity of 32 to 38 sec/quart.

The porosity of the earth formation in which the well is to be drilled determines the viscosity of the mud that must be used as a drilling fluid. If ordinary clay of good quality is available, it may be mixed with water to prepare the drilling mud. As long as this mixture functions satisfactorily, it is not necessary to use a commercial mud preparation. If zones of lost circulation are encountered or if the consumption of drilling fluid becomes excessive, prepared mud or other substances such as finely chopped straw may be added. If the earth formation near the surface is clay, the well may be started with clear water as drilling fluid. The water will mix with the clay in the drill hole to form the necessary circulating fluid. Drilling may be continued with only this natural mud, until a lost circulation zone is encountered and the consumption of drilling fluid becomes excessive. When this occurs, it is necessary to add commercial mud (bentonite) to the drilling fluid.

Sand Content

Sand content affects mud density and apparent viscosity, mud pump wear, bit life, drilling rate and formation damage. Sand content is measured by carefully washing a measured volume of mud on a 200 mesh screen. The material held on the screen is poured into a cone shaped graduated container. The maximum desired limit is 2% by volume.

Filter Cake

When the drilling fluid is in the bore hole, pressure in the annulus tends to force it into any porous formation. Clay platelets build up on the formation and reduce fluid loss. This build up of clay is called the filter cake (mud cake). Some water filters through the cake and it is water loss while loss of both clay and water is mud loss. It is desirable to maintain a thin, easily removed filter cake while minimizing water loss and maintaining circulation.

Gelling

One of the properties of a bentonite and water mixture, is its ability to gel. The mixture is fluid while being stirred, but stiffens after standing. When stirred again, it becomes a fluid. This property helps suspend drill cuttings during non-circulation periods.

The drilling fluid is usually prepared in pits before starting the drilling operation. After the fluid is mixed, sufficient time must be allowed to elapse to ensure complete hydration of the clay prior to its being circulated into the hole (Driscoll, 1986). If this is not done, the clays may swell in the hole or in the aquifer itself. As a result, it may be impossible to remove them after the casing is installed and the well may never reach its potential yield.

Drilling Procedure

After the rig has been properly erected and its alignment checked, it is ready for drilling. The bentonite drilling mud is sprinkled into the suction pit. Water is filled in the pits and the drilling mud mixed thoroughly to form a pasty solution. The pump suction line is then immersed in the suction pit and the foot valve held in position with a rope. The foot valve is held above the bottom of the pit but below the water level in the pit. This facilitates continuous suction of the drilling fluid.

A pilot hole opener of about 15 cm diameter is placed over the base or pedestal plate and the drill head moved forward to bring it exactly above the centre line of the pilot hole. The drill head (kelly) is pulled down to bring the sub end of the kelly over the bit. A band of cotton thread is placed between the threaded end of the bit and the sub before it is screwed to the bit. Rotary motion is then applied to the kelly with a downward motion. Simultaneously, the mud pump is operated to provide a continuous flow of drilling fluid. When the kelly has penetrated a depth of 6 m, it is taken out, the bit unscrewed, and a stabiliser of 3 or 6 m length interposed between the bit and the kelly. The pilot hole opener is replaced with a 15 or 25 cm diameter drag-type bit. As the bit rotates, it cuts and abrades the formation into small particles. Removal of drill cuttings is effected by the mud laden fluid, kept under constant circulation by the mud pump. The drilling mud moves under considerable pressure from the mud pump to the drill pipe and to the bit. It streams out through the jetting nozzles of the bit at a high velocity and picks up the drill cuttings. Deflected upward from the bottom of the hole, it travels through the annular space between the drill pipe and the walls of the drilled hole. At the ground surface, the drilling mud with cuttings is let away from the drilled hole, through a suitable open channel, to the settling pit. It overflows from the settling pit to a suction pit where it is picked up in the suction hose of the mud pump to repeat the cycle. The procedure of drilling is continued, till another 6 m depth of hole is drilled. Additional drill rods are interposed between the stabiliser and kelly, as drilling proceeds. By continuing this operation, a depth of bore hole to adequately tap the aquifers is obtained. The drilling rods and bit are removed. The bore is developed into a production hole by reaming, which is identical to the drilling operation, except that bigger diameter bits are used. Samples of the excavated material (cuttings) escaping with the drilling mud to the ground surface are washed and kept in a sampling box, in different compartments. A strata chart is prepared to design the assembly of the tube well.

Drilling in Alluvial Soils

While drilling in unconsolidated alluvial formations, the load on the drill bit as well as on the power transmission system is low. Hence, drilling can be done at high speeds. Moreover, a drag bit can be used for fast work. However, when drilling at a depth beyond 60 m, special care is necessary, since the drilling tool works under a heavy load.

In clay strata, the speed should be slowed down, depending upon the load on the tool. This can be effectively ascertained by the operator. As drilling proceeds at higher depths, the consistency of the drilling fluid should be maintained by adding fresh bentonite. Drilling at greater depths requires vigilance and alertness on the part of the operator. He should ensure that the cuttings are passing through the discharge drain. In case no cuttings are coming out, it implies that either the mud pump is not effectively supplying drilling fluid, or the bit is not cutting properly. Under this situation, the drill rods should be taken out, the bit replaced by a newly dressed one, the drill rods lowered again, the bore washed, and drilling continued with care and caution.

Drilling in Sandstone

While drilling in hard formations, it is better to use rock-roller bits in place of drag-type bits. Further, the speed of rotation of the kelly should match the progress obtained, depending on the hardness of the material being penetrated. Any carelessness on the part of the operator may result in the cracking of the kelly and breakage of the power transmission system. Excessive load on the bit causes heavy torsional stresses in the rotating mechanism. Hence, the speed of cutting should synchronize with the various functional variables such as hardness of the rock, sharpness of the teeth of the bit, depth of drilling, and viscosity and velocity of drilling fluid. It is advisable to stop the rotary motion of the kelly and allow washing of the drilled bore hole for a few minutes after every 3-5 m progress in drilling. This will ensure a clean bore hole and prevent clogging of the bit by cuttings. When the progress becomes too slow to be economical, all the drilling rods should be taken out and the bit replaced by a newly dressed one. When sufficient bore hole depth, as per the aquifer thickness, has been obtained, all the drilling rods are taken out. The bit is removed and the bore developed into a production hole by reaming. Further, as the diameter of the hole keeps increasing, the demand for drilling fluid increases, which calls for slower speeds of rotation. After the production hole is obtained, the pipe assembly is designed as per the thickness of aquifer available, static water level, anticipated drawdown, seasonal variations in water levels, and size of pump to be installed. The pipe assembly is lowered into the bore and the annular space between the walls of the hole and assembly packed with gravel of suitable size.

Fishing Tools

Sometimes, a drill pipe may break. This may be due to the shearing of the pipe or breakage of the coupling. Sometimes a drill pipe may be dropped accidently into the hole. Appropriate fishing tools are used to pull it out of the hole. A variety of tools have been developed for use in fishing jobs. The important ones among them are the tapered tap and die overshot. Recovery of lost drill rods depends upon whether the driller can set the tool down on top of the rods and connect them. The tapered tap and die overshot are simple tools, usually effective only if used immediately after failure occurs. In holes where the drill pipes have become 'frozen' from cuttings settling around them, circulation of drill fluid to the bottom of the hole is helpful in loosening them. In this case, another important fishing tool, called the circulating slip overshot is used. Circulating slip overshots, after gripping the top of the pipe, enables the circulation of drilling fluid through the pipe. In some cases, the use of a rotary jar immediately after the overshot becomes essential to exert jarring blows on the jammed object (Details on fishing tools and their operation are presented in Ch. 7).

5.4.4 Capacity Range and Adaptability of Rotary Rigs

Based on their capacity, direct rotary rigs may be classified into three groups, viz., (i) light rotary rigs, (ii) medium rotary rigs, and (iii) heavy rotary rigs. Rotary rigs with the rated maximum hook-load capacity, up to about 9000 kg, and capable of drilling slim (pilot) holes with 6 cm drill pipes, up to about 380 m, may be considered light rigs. These are suitable for drilling and completion of light-capacity tube wells (upto 30 1/s discharge) to depths up to 60-140 m or so, in alluvial and semi-consolidated formations. Their average performance may range between 5 and 30 m per day, depending on the size and depth of the bore and the type of formation, the rate of progress being slow in hard formations.

Medium direct rotary rigs have a rated maximum hook-load capacity up to 13,000-18,000 kg and are capable of drilling pilot holes upto depths of 450-700 m, using 6-7 cm drill pipes. These rigs are suitable for drilling and completion of medium-capacity tube wells (30 to 60 1/s discharge) to depths upto 30-250 m or so, in alluvial or semi-consolidated formations.

Heavy-duty rotary rigs have a maximum hook-load capacity of 22,000 to 45,000 kg. They are capable of drilling pilot holes up to 750-1000 m, using 9 cm drill pipes. These rigs are capable of drilling heavy-capacity tube wells (60–150 1/s discharge) up to depths of 225 m and above in alluvial and semi-consolidated formations.

The direct rotary method is most suitable for drilling deep holes in unconsolidated formations. However, it is uneconomical for drilling in boulders and hard rock strata, due to slow progress and high cost of bits. It is also unsuitable for drilling in slanted and fissured formations and serious lost-circulation zones. The mud cake formation along the walls of the hole requires greater efforts for well development. Accurate strata sampling becomes difficult due to the mixing up of cuttings with sand and clay from various strata, and because of the time lag between the actual cutting and the removal of the formation material to the ground surface.

5.4.5 Drilling Problems in Direct Rotary Drilling

The drilling with direct rotary drilling presents many problems. Common problems include:

Lost Circulation

Lost circulation is the loss of drilling fluid from the hole through porous formations, cracks and crevices. It can be partial or complete, depending on the conditions. When circulation is lost, the drilling fluid is not performing one of its major functions, that of transporting the cuttings up the hole where they can be released in the mud pit. If the cuttings are not removed from the hole; they will pack around the drill string above the pit, resulting in stuck pipe and possible loss of the bit, collars, and part of the string.

If drilling fluid is suddenly lost, immediately switch the valve to direct the drilling fluid back to the mud pit through the by-pass hose to minimize the loss of water. Then quickly pull-up the drill 1-2 m from the bottom of the hole so that it is likely to become jammed if the bottom portion of the hole collapses. If drilling has been proceeding with water or natural mud, replace the fluid with a thick bentonite slurry, circulate back down the hole and let it sit for a while. This will allow the fluid to gel in the formation and provide a seal sufficient to allow circulation to be restored.

The "gunk squeeze" method of sealing off a zone of lost circulation involves forcing a large amount of clay or cement into the zone of water loss (usually at or near the drill bit) and forcing it into the formation where it swells and fills-up and cracks (Australian, 1992).

If the lost circulation zone cannot be blocked, drilling sometimes may proceed without return circulation. Alternatively, casing can be placed to seal-off the problem zone. If none of these options work, it may be necessary to abandon the hole or to continue drilling using air rotary drilling machine.

Bore Hole Caving

The drilling fluid prevents caving of the hole because it exerts pressure against the wall. As long as the hydrostatic pressure of the fluid exceeds the earth pressures and any confining pressure in the aquifer, the hole will remain open. The pressure at any depth is equal to the weight of the drilling fluid column above the point.

The main cause of hole caving is lack of suitable drilling fluid. This often occurs in sandy soils. In such soils, bentonite must be mixed with drilling water to increase its viscosity and keep the bore hole from collapsing.

Bore hole caving can also occur if the fluid level in the hole drops significantly. To minimize caving risk, keep the drill pipe in the well (several meter off the bottom) and refill the well through the drill pipe. Pouring fluid directly into the hole may trigger caving. If caving occurs while drilling, check if cuttings are still existing in the well. If they are, stop drilling and circulate drilling fluid for a while.

Sometimes part of the hole caves while the casing is being installed, when this occurs the casing must be pulled out and the well re-drilled with heavier drilling fluid.

Drill Bit Jamming

The drill pipe and bit may become jammed when the drilling fluid is not allowed to thoroughly clean the hole prior to stopping to add another joint of drilling pipe or the fluid is too thin to lift gravel from the bottom of the hole. Therefore, if the drill bit starts to catch when drilling, stop further drilling and allow the drilling fluid to circulate and remove accumulated cuttings from the hole. Then continue to drill at a slower rate. If it continues to get catch, thicken the drilling fluid.

If the drill bit and pipe become jammed, stop drilling and circulate drilling fluid until it is freed. If circulation is blocked, try to winch the bit and pipe out of the hole. Stop the engine and use a pipe wrench to reverse rotation (no more than one turn to prevent unscrewing of the rod). Rapidly hit the drill pipe with a hammer to try and jolt the bit free.

If these actions are not successful, use lengths of drill pipe without a bit attached to 'jet out' the cuttings. Attach the pipe directly to the discharge hose from the mud pump. Thicken the drilling fluid to ensure that the cuttings holding the bit can be removed. Then place tension on the stuck pipe with the drill rig winch. Once fluid starts to circulate out of the hole, slowly push the jetting pipe down the hole beside the jammed drill pipe until the bit is reached. When fluid starts to circulate out of the stuck pipe and/or loosens, pull the stuck drill and resume circulation of the thickened drilling fluid back down the drill pipe and bit. Remove the jetting pipe. If water freely circulates out the hole, slowly lower the drill pipe and bit and resume drilling.

Drilling Fluid Backflow

Sometimes drilling fluid comes up through the drill pipe when the swivel is disconnected. This is caused by falling soil particles pressurizing drilling fluids at the bottom of the hole. Immediate action is required because this occurs when either the hole is caving-in or when drill cuttings have not been cleaned well enough from the hole. If backflow of drilling fluid is noticed, immediately re-connect the drill pipe and continue circulation to clean-out the cuttings. If caving is suspected, thicken the drill mud while continuing circulation.

Casing Jamming During Installation

Sometimes it is not possible to lower the casing and well screen to the bottom of the hole. This can be due to part of the hole collapsing, clays in the aquifer swelling and reducing the size of the hole or the hole being crooked resulting in the casing digging into the wall of the hole. If the casing does not slide freely into the hole, it is not advisable to try and force the casing down. Striking it hard in an attempt to drive it may cause the screen to deform, rotating and pushing it down can cause the screen openings to become clogged with fine materials.

To avoid these problems, minimize the amount of pull-down pressure when drilling so that the bit can run freely under its own weight. When the casing has jammed, the best solution is to pull the casing/screen from the hole. Slowly redrill the hole with a large diameter reamer bit, concentrating on the portion of the bore hole where the casing jammed.

5.4.6 Principles of Reverse Circulation Hydraulic Rotary Drilling

A reverse circulation rotary drill works on the same principle as the direct rotary method, except that the drilling fluid is circulated in the reverse direction to that of the direct rotary method (Fig. 5.31). The drill fluid, which is generally clear water, is fed from a tank down the annular space between the hole and the drill pipe and is recovered along with the drill cuttings through the drill pipe, generally by means of a centrifugal pump. It is discharged into a settling tank where the cuttings are allowed to settle. The process is continuous. The hole is not cased during drilling and is prevented from cave-in by the hydrostatic pressure of the drill fluid in the hole and the film of fine-grained material deposited on the wall of the hole by the circulating water. A considerable supply of water, in the range of 3-9 1/s, depending on the size and depth of the hole, is required from the time drilling is started till the gravel packing of the well has been completed. Mud is added to the water if the formation starts to cave-in. The drilling operation has to be carried out round the clock. For drilling deeper holes, up to 300 m or so, compressed air is used for circulating the drilling fluid.

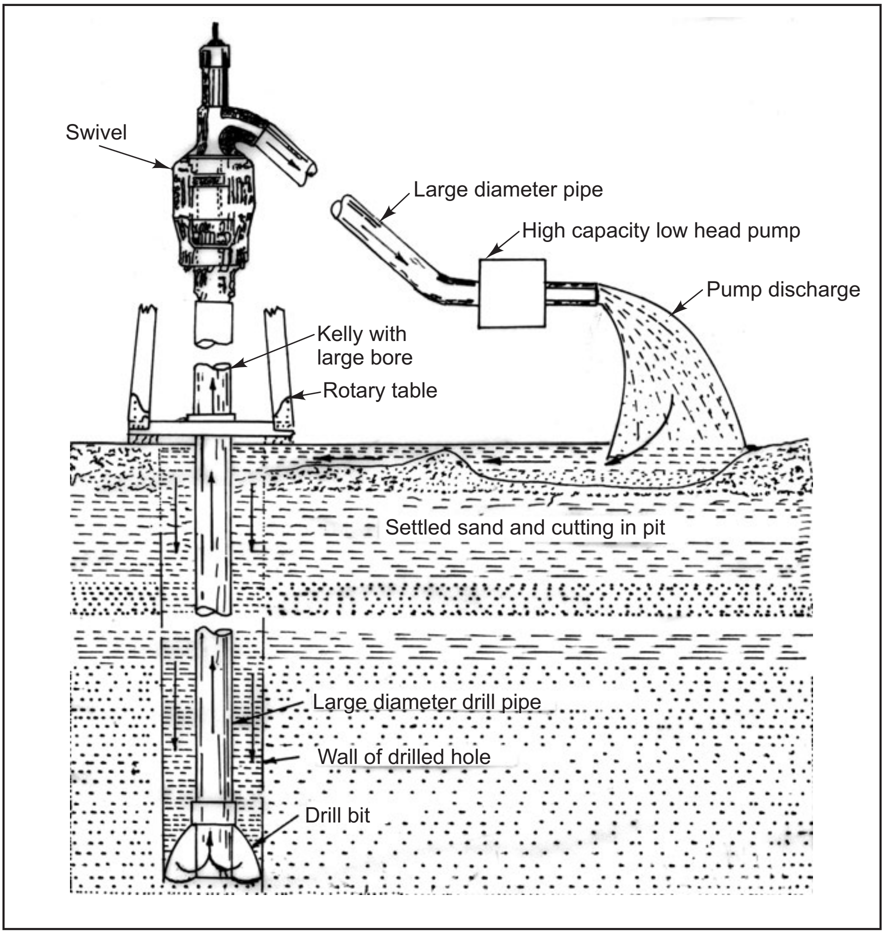

Fig. 5.31 Schematic sketch illustrating basic principles of reverse rotary drilling

5.4.7 Reverse Rotary Drilling Rig

Reverse circulation rigs (Fig. 5.32) differ from direct rotary rigs in the following respects: (a) the rotary table has a lower speed range and fewer number of speeds, (b) the drill pipes used are usually larger in size and flange jointed, (c) the pump used is centrifugal provided with non-clog impellers, and (d) air lift pumps are used in heavier rigs for drilling to deeper depths. A 15 cm diameter pipe is commonly used so that stones up to 12 cm in diameter can be pumped out through the pipe. The drag bit used with a reverse rotary rig has a larger diameter opening to ensure the unrestricted movement of stones along with the drilling fluid. The following are the constructional details of reverse rotary drilling rigs.

Fig. 5.32 Reverse circulation rotary drilling in progress. Note the water storage-cum-settling pit in the foreground

Draw Works

It is the controlling centre on the rig platform from which the driller operates the rig. It usually consists of two drums to hold the drilling string and handle auxiliary equipment. Steel wire rope of sufficient length and capacity is rolled on both the drums. The operation of the drums is controlled through clutches. The drive is given through the transmission to provide varying speeds for the pull.

Mast

The mast is made of horizontal sections with cross bars welded to the sections at intervals of about 3 m. It is provided with a mechanical lock to hold it in a vertical position. Adjustable leg supports are provided to take up the load without any disturbance to its position. The mast is fully equipped with attachments for all the hydraulic and water connections, crown pulleys, wire string and suitable wiring arrangements for lighting. The raising and lowering of the mast is carried out through double acting, hydraulic cylinders (one or more), with safety checks. The hydraulic cylinders are operated with a hydraulic pump, driven by the main power unit and controlled by valves.

Rotary Table

The rotary table is used to give positive rotation to the drilling string, at various speeds, to meet the different strata conditions (sand formations require slower rotational speed, while clay formations require faster rotational speed). The variation in rotational speed is provided through the transmission unit. The rotary table is gear and pinion driven, completely immersed in lubricants, and totally enclosed, preventing entry of mud, sand and grit.

Transmission

The transmission consists of a gear box, with not less than 4 foreward speeds and one reverse speed, with the required gear reduction. It is coupled to the power unit through the main clutch. The transmission unit is leak-proof and filled with a suitable grade of lubricating oil. It ensures different rotational speeds for the rotary table according to the strata conditions, and different hoisting speeds according to the load on the hook.

Pump

The pump is used to remove the cuttings as the drilling progresses, to obtain the maximum rate of drilling. It is designed to pass solids upto 15 cm diameter, even at great depths. A suitable stuffing box is provided for efficient sealing against suction leakage and an extra vacuum pump is provided for priming the pump.

Power Unit

The rig is usually operated by the same engine fitted to the truck chasis, through a specially designed gear box. The diesel engine is of adequate power to meet all the requirements. It is provided with a fuel tank of suitable capacity.

5.4.8 Operation of Reverse Rotary Drills

The crew required to operate the reverse rotary drilling rig is the same as described for the operation of direct rotary drilling rigs (Art. 5.4.3). The various steps for tube well drilling, using a reverse rotary rig, are as follows:

Water Storage Pits

Water storage pits are constructed for storage of water and settling of the formation material pumped out. The size of each tank should be at least 3 times the volume of the proposed well bore. The tanks have to be kept full of water during drilling, lowering of the well assembly and gravel packing. An essential requirement in reverse rotary drilling is that the pressure head of drilling water in the bore hole must be sufficiently greater than the pressure head of the ground water in the aquifer, in order to avoid caving in. Further, since circulating water is lost from the hole into the permeable formations a considerable supply of water is required.

Setting Up the Drilling Rig

After the pits are ready, the rig is placed at the site where the well is to be drilled. It is located in such a way that the centre of the rotary table is exactly above the point where the bore hole is to be drilled. The rig is jacked and levelled. Proper packings with wooden sleepers should be provided under the jack screws. The earth under the rig is well compacted so that, during the drilling operations, its level and alignment are not disturbed.

After jacking up the rig, the derrick is erected slowly and gently. The rotary and main transmissions should have their first gears engaged for this purpose. After the derrick is fully erected, it should be locked in position with the help of two latches provided for this purpose. At this stage, the level of the rotary table should be checked again and adjustments made, if necessary.

Drilling Fluid

The drilling fluid comprises water. Usually, no drilling mud is used. However, the water used for circulation may pick up suspended clay and silt from sub-surface formations, as drilling proceeds. To prevent caving in of the hole, the fluid must be kept at ground level at all times. The hydrostatic pressure of the water column plus the inertia of the body of water moving downward outside the drill stem support the bore hole wall.

Drilling Procedure

After the rig has been properly erected and its alignment checked, dry drilling is done with an earth auger of suitable size fitted on to the kelly (Fig. 5.33). During dry drilling, the rotary table is worked slowly in the first and second gear. The driller takes care that the auger is not allowed to work below

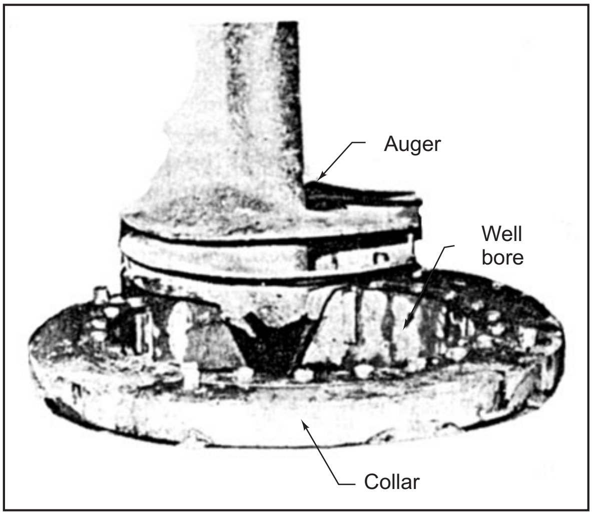

Fig. 5.33 Earth auger being lowered for drilling a dry bore, using a reverse rotary drilling equipment

ground for long, and is taken out after drilling about 30 cm at a time, cleaned and re-lowered for further drilling. The process is repeated till the flange of the outer kelly rests on the rotary table and the kelly bend is easily connected with the suction pipe bend of the pump. On completion of dry drilling, the auger is removed from the kelly. A liner (steel pipe), with a provision for side entry of water and of diameter equal to the size of the bore is lowered into the dry bore (Fig. 5.34). This protects the dry hole. A drag bit of the required size is attached to the kelly. It is then lowered in the hole (Fig. 5.35) and the kelly bend connected with the suction pipe bend of the pump. Water from the storage pit is allowed to flow into the hole by gravity.

After the bore hole is filled with water, the pump, sluice valves and suction pipe are closed and water filled through the discharge pipe upto its mouth. Care is taken to keep the wheel valve on the body of the pump open so as to let the air in the pump pass through it. When the pump is filled, water will begin to flow through the wheel valve. At this stage the valve is closed. The pump is then put into commission by engaging its clutch, and the sluice valve on the auxiliary suction pipe is opened. Both these operations are carried out simultaneously and the pump starts discharging water. It is allowed to work for a few minutes like this. When the vacuum gauge on the suction pipe shows a vacuum of 50 to 65 cm, the suction valve is opened slowly so that air in the suction pipe and kelly escapes. The pump is allowed to run for a few more minutes so that a vacuum is created in the suction pipe as well. The sluice valve is then opened fully. At this stage, the pump starts lifting water through the suction pipe also. When full discharge is available through the suction pipe only, the sluice valve is closed.

Drilling is started by rotating the tool with the rotary table. Drilling by the reverse circulation method can be started only when an artificial water head of not less than 2 m can be maintained on the natural water table. With this method it is possible to drill large diameter holes (even up to 1.5 m dia.). The velocity of the drilling fluid entering the concentric space through gravity is low. Water is drawn up the drill pipe by suction, at a velocity high enough to carry to the surface all the debris, including boulders within the limit of the inside diameter of the drill pipe. The debris removed at the point of drilling are brought to the surface slowly and without any contamination from other strata. Hence, the samples represent the true characteristics of the formation.

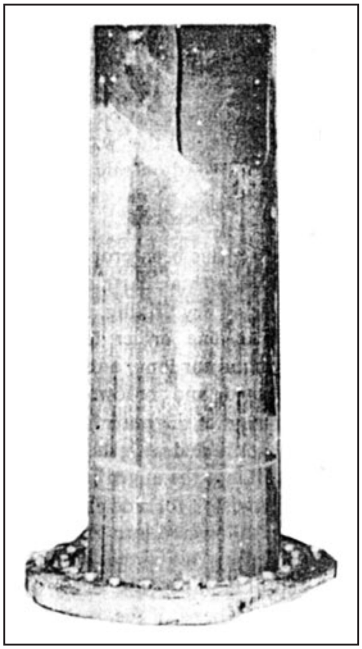

Fig. 5.34 Lowering of a liner into the dry bore during the initial phase of drilling with a reverse rotary rig

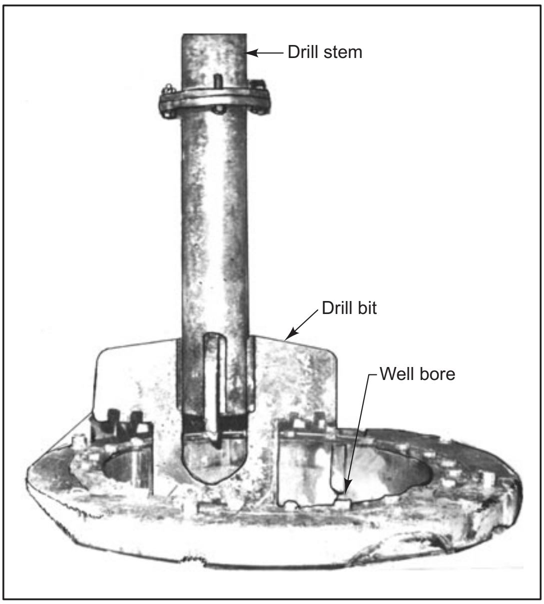

Fig. 5.35 Lowering of a drag bit to the bore for reverse rotary well drilling

When drilling is started, there is little load on the drilling tool. Hence, the drilling-drum brake is made free so that the drilling tool, under the load of the inner kelly, starts cutting the strata. During drilling, a helper is assigned to the discharge point of the pipe to watch the strata. On any change, the strata being pumped out along with water, is collected in a bucket. After draining out the water, the strata samples are kept in a sampling box, as explained under direct rotary drilling. A proper record in respect of the depth of each strata is maintained.

When the inner kelly sinks fully, the rotary table is stopped but the pump is kept running for a few more minutes till no further cuttings are noticed. It is then stopped and the valve closed. The kelly is lifted up after disconnecting its bend from the suction pipe bend. The drilling tool is disconnected from the kelly and a 3 m long drill pipe is added to the tool. The kelly is then reattached and lowered. After the outer kelly has been lowered, the kelly bend is reconnected with the suction bend. The pump is reprimed and drilling resumed.

Drilling in Alluvium

While drilling in alluvium, the rotary table can be worked in the third or even fourth gear. However, when drilling at a depth beyond 80 m, special care is necessary, since the drilling tool works under the heavy load of the drill pipes and is liable to get choked with cuttings. In a clay strata, this trouble may become so serious that it becomes difficult to release the tool. This necessitates taking out the drill pipes and cleaning the bit. Hence, a little carelessness on the part of the operator costs valuable drilling time.

Drilling at greater depths requires vigilance and alertness on the part of the operator. He should watch that the cuttings are passing through the discharge pipe. When no cuttings are noticed, the rotary table should at once be put out of commission, the tool slightly raised and the pump allowed to run. After sometime, the cuttings will start passing through the discharge pipe. When the bore is cleaned and the gauge indicates full vacuum, the drilling bit is re-lowered and drilling restarted with care.

Sometimes, during drilling, the suction line of the pump develops a joint leakage and the pump does not work at its full capacity. In such a situation, the vacuum gauge will show full vacuum and the cuttings, instead of rising up and passing through the discharge pipe, may start falling down in the hole. To overcome this difficulty, the pump is put out of commission and the drilling tool raised to check all the joints of the suction pipe to detect leakage. The leaky joints are tightened. The pump gland is also checked and set right, if necessary. When set, the vacuum gauge will show full vacuum and the pump will work at its normal capacity.

Drilling in Sandstone

While drilling in sandstone, the rotary table is rotated very slowly, as otherwise the bolts of the drilling tool and drill pipes get loose and are likely to break, and the tool itself wears out. Sometimes, in sandstone, the tool does not work with ease. This results in a heavy load on the rotary table. In such a case, the rotary table is disengaged immediately and the tool raised by a few centimetres. The rotary table is then worked slowly and the tool fed suitably, so as to enable it to work easily.

A little lapse on the part of the operator, while drilling in sandstone, will result in the cuttings getting stuck in the drill pipe or in the bend of the kelly. This results in the blockage of the passage and the pump discharge falls down considerably. At this point, the operator will have to take out all the drill pipes, clean them and re-lower them. This results in wastage of time and heavy cost.

Sometimes the sandstone is so hard that continuous effort for hours will fail to pierce through the same. The tool gets worn out and does not cut the sandstone. When such a situation arises, the operator should stop the drilling and complete the hole with the available strata, or abandon the hole if there is not enough aquifer.

5.4.9 Adaptability of Reverse Rotary Drilling

Conditions that favour the use of reverse circulation method of drilling are sand, silt or silty-clay formations and the absence of boulders of diameter more than 12.5 cm. The rate of drilling is much faster than other methods of drilling. The strata sampling is more accurate as compared to direct rotary drilling. It is one of the most economical methods of drilling.

The following conditions may limit the use of the reverse rotary method:

1. Too high static water level
2. Lack of adequate water supply to supplement the drilling fluid
3. Stiff clay or shale formation
4. Considerable number of cobbles or boulders of diameter larger than the drill pipe or the openings in the drill bit

5.4.10 Drilling Problems in Reverse Rotary Drilling

Underground strata vary from place to place. Each stratum possesses its own characteristics and requires different treatment. A good driller diagnoses the drilling problem from observations of the discharge coming out of the discharge pipe and determines the treatment to be given.

Drilling through Clays which Cave-in

Sometimes, a driller is confronted with the problem of drilling through clays which cave-in. Such clays are generally dry and hard to pierce through. When such a stratum comes into contact with water, it dissolves and starts falling. A negligent driller is taken unawares and finds his tool stuck. Hence, in a collapsing stratum, further drilling is not attempted. Instead, the tool is raised. Drilling mud is mixed in a separate small tank so that it becomes a thick paste which can be poured into the bore hole by means of buckets. The quantity of drilling mud to be mixed depends upon the depth where such a stratum has been met and its nature. During mud mixing, the rotary table is not operated and the tool is not rotated. While mud circulation is in progress, the discharge coming out of the pipe should be carefully watched to assess the quantity of collapsed material escaping. In case of a heavy cave-in the bore hole gets filled with the collapsed material, all of a sudden. In such a situation, the discharge of the pump falls down at once. The pump is immediately disengaged, the kelly lifted and a couple of drill pipes, as warranted by a particular situation, removed and mud circulation started. Mud circulation should be continued as long as cave-in continues.

The collapsed material should be cleared by operating the rotary table at low speed, with small feeds. Any lapse may block the drilling tool and render it difficult to release. The entire string of drill pipes will then have to be taken out to clean the tool. This consumes considerable drilling time and adds to the cost of well construction.

The collapsed material should be cleaned carefully. If this strata is followed by a clayey one, the tool should be worked at low speeds. The driller should ensure that cuttings are continuously escaping through the discharge pipe.

Chemical Treatment

Caustic soda is sometimes used in the drilling fluid to raise its *p*H to about 10.5 and prevent cave-in. The practice is successful if the clays are wetted in their natural condition. Dry porous clay and shales do not stabilize with increased *p*H. Sodium silicate, in the ratio of 4-10 per cent of the volume of the drilling fluid, may be effective with clays and shales. If the clay layer is thin, the treatment can be carried out directly at the hole. If the layer is relatively thick, all the fluid should be treated.

5.4.11 Air-Injection Equipment for Reverse Circulation Drilling

The pumping efficiency of a reverse circulation system begins to reduce at a depth of approximately 180 m. A reduction in the upward velocity of the drilling fluid is caused by the increased friction of the fluid in the drill stem. As the velocity decreases, it becomes increasingly difficult to raise the cuttings and progress is slow. With the addition of a well-designed air-injection system, it is possible to drill satisfactorily upto about 225 m. Some drillers have reported depths of 250 to 300 m with a 15 cm drill stem.

Although there are many areas where the required depth does not exceed 150 to 180 m, the various advantages gained by air injection include:

1. increased speed of drilling allows faster hole completion with the possible elimination of cave-ins,
2. much less drilling water is used (the large volume of air in the drill stem decreases the amount of water being circulated), and
3. priming of the system is eliminated.

The air-injection method is essentially an air-lift pumping system. External air lines on the drill stem and kelly, leave the inside of the column completely open for high velocity upward movement of the drilling fluid. To start with, the hole is drilled to about 15 m with a regular circulating pump and priming system. At that point, 2 or 3 lengths of the drill stem are pulled out and the air manifold inserted. Drilling is then resumed and the drilling fluid discharged into the pump through a pump by-pass line. Once the air flow is started the pump is disconnected. Air from an air compressor is injected at the top of the kelly and carried below water. Air enters the drill stem, making the fluid above that point less dense than the fluid outside the drill stem. This results in high-velocity, upwards flow of water with the cuttings.

The maximum depth of air injection into the manifold depends on the capacity of the air compressor available. Normally a 10 kg/cm^2 air compressor is adequate, allowing a maximum manifold submergence of 80 m. When the manifold reaches this point, 2 or 3 lengths of drill stem are pulled out, another manifold section put in the line and the tools again lowered to the bottom. Air is again injected at the 10-15 m submergence level and drilling resumed.

A greater drilling speed is obtained by a sustained high velocity of the drilling fluid, regardless of the depth. However, pipe friction limits the working depth, for a 15 cm drill stem, to about 250–300 m. Greater depths, upto 350 m, are obtainable with a 20 cm drill stem.

Existing drill stems can be adapted for continuous use by using the air-injection technique. Usually, two air lines of steel pipes are welded to the outside of each drill stem. Suitable gaskets are used at each flange to prevent the escape of air. Satisfactory results can also be obtained by carrying air to the manifold in a double-walled pipe with an air space between the inner and outer pipes.

5.4.12 Dual-Wall Reverse Circulation Rotary Drilling

The dual-wall reverse circulation rotary method employs a double-wall drill pipe. The inner casing rotates, acting as drill pipe, while the outer pipe acts as casing (Fig. 5.36). Air or water is forced down the outer casing and circulated up the inner drill pipe. Cuttings are lifted upward through the pipe to the

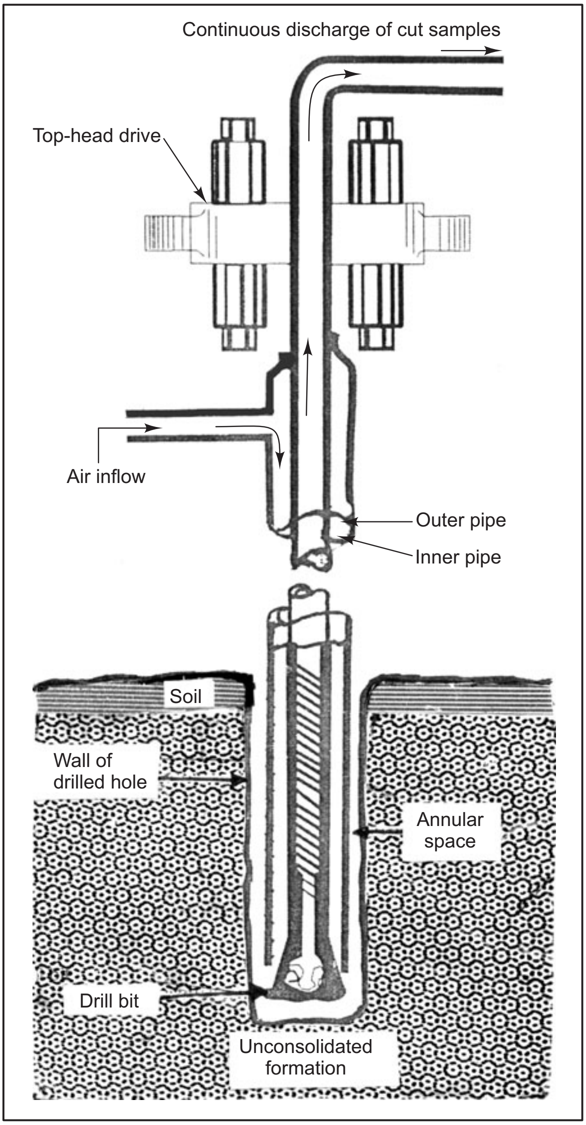

Fig. 5.36 Diagram illustrating the dual-wall reverse circulation method
Source: Based on Driscoll (1986)

surface. Either a hammer or bit can be used to cut the formation. The outer casing allows for stabilization of borehole, prevents caving around the bit, minimizes cross-contamination from cuttings, and allows minimal vertical contaminant migration. The primary advantage of the dual-wall method is that it allows continuous sampling of the subsurface material and eliminates problems associated with lost circulation and borehole instability. The method is applicable in any type of geologic formation and does not require the use of surface casing. In general, hole diameters do not exceed 30 mm and depths in excess of 400 m can be reached.

5.4.13 Periodical Inspection and Maintenance of Rotary Drilling Rigs

A regular and planned inspection of all moving parts should be made at least once during each operating shift of a drilling rig. The parts of the machine which are not functioning properly should be attended to and set right. Any negligence may become so serious that the machine will have to be shut down for general repairs. Maintaining a proper log book and filling its columns regularly are essential. In addition to making the daily inspection of all moving parts, the following inspection schedule is recommended:

A. Shift-Wise Inspection

1. Check the level of the rig frame and the verticality of derrick with the help of a spirit level and correct by screw jacks, if necessary.
2. Check all the wire lines to see if any strand is damaged. Change the wire line, if necessary.
3. Check and tighten, if necessary, the U-clamp nuts on the wire line ends fastened to the drum flange and the crown block of the derrick.
4. Check and tighten, if necessary, the foundation bolts of all the mountings.
5. Check the water level in engine radiator and fill, if necessary.
6. Grease the swivel bearing.

B. Daily Maintenance

1. Check oil levels in the following and top up to the recommended levels, if necessary.
   (a) Chain wheel box
   (b) Rotary transmission
   (c) Draw works chain drive case
   (d) Rotary table
   (e) Engine
   (f) Main transmission
   Drain out the used oil, if found dirty, and flush with flushing oil. Use only recommended oils.
2. Check all the bolts of the propeller shaft flanges and tighten, if necessary.
3. Check and adjust brake straps and their connecting links and pins to ensure safe braking of drums.

C. Weekly Maintenance

1. Check and adjust the tightness of V-belts to prevent slippage (remember that the V-belts wear fast if they are either too loose or too tight).
2. Check all the moving parts of operating levers, linkages and controls and adjust and grease, wherever necessary.
3. Grease all the wire ropes and check for any worn out or broken strands.
4. Check and adjust the clutches for their proper functioning.

D. Maintenance of Bearings, Engine and Truck Chasis

1. All the bearings are provided with grease seals to preserve the grease within the bearing housings. It is, therefore, not necessary to grease them often. They should be greased only at an interval of 4 to 6 months or at the time of general over-hauling or repairs.
2. Reference should be made to the service manual of the engine and truck chasis for their maintenance schedule.

5.5 DRILLING WITH DOWN-THE-HOLE HAMMER AND AIR ROTARY DRILLS

Percussion and rotary methods of well drilling are usually uneconomical in water well drilling in hard rock areas due to the slow penetration rate, high bit cost, and high maintenance cost of the machinery. Air-operated down-the-hole (DTH) drills and air rotary drills have proved to be the best for the construction of water wells in hard rock areas. Drilling with DTH machines combines the percussive action of percussion drilling and rotary action of rotary drilling. The tool is essentially a pneumatic hammer attached at the end of a drill string. The hammer tool comprises an air-operated piston, striking directly on the bit at a high frequency, while the entire assembly is hydraulically pressed against the rock. By rotating the drill string at the same time, a hammering action is imparted to the full surface of the bottom of the hole, which pulverises the formation. The air admitted for the hammering action, is allowed to escape at the bottom of the hole, to lift the cuttings up to the surface through the annular space between the hole and the drill string.

With DTH drilling, faster penetration results because the hammer at the bottom of the hole allows the piston to transmit the blows directly on the bit, without losing its energy through the drill string. The hammer may drill granite 2-3 times faster than the air rotary method and several times faster than the percussion method.

The operation of the bit depends upon the capacity of the air compressor, the design of the hammer, the type of bit and the type of coolant used in the drilling operation. An air compressor continuously provides the required quantity of air to operate the hammer as well as clean the cuttings. A straight hole is ensured by the short rapid blows which minimise the effect of chipping and breaking the formation. DTH drilling, however, is limited to constructing small diameter wells. The largest drill bit commonly used is 15 cm. However, the well size can be larger (about 30 cm) when rock-roller bits are used. Difficulties are faced in drilling in formations with large air pockets and deep water columns.

To remove the cuttings effectively, air velocity in the annular space should be maintained between 600 and 1500 m/min. An annular space air velocity of about 900 m/min is usually recommended. Excessive air velocities can cause hole enlargements in certain formations. Relatively small back pressures on surface equipment can significantly reduce the annular air velocity near the surface.

5.5.1 Air Rotary Drilling

In air rotary drilling, compressed air is used as the drilling fluid, rather than drilling mud. In this well drilling method, air is circulated through the drill pipe. It escapes out through pores in the drill bit and moves upward in the annular space carries the drill cuttings to the surface or blows them out into rock crevices.

Air rotary drilling is limited to consolidated materials. Air rotary drilling machines are usually equipped with a conventional mud pump in addition to a high-capacity air compressor. Drilling mud can be used in drilling through caving materials above bed rock. Roller-type rock bits, similar to those designed for drilling with mud fluid, can be used when drilling with air. Three-cone rock bits up to about 30 cm diameter are commonly employed.

The air rotary method usually results in faster penetration in hard rock formations, compared to the conventional hydraulic rotary method. Loss of circulation does not prevent drilling. Accurate strata sampling is possible. The main limitation is the large quantity of air required for drilling. Difficulties are also experienced in tackling caving formations. Therefore, pneumatic direct rotary drilling has been mainly used for drilling small diameter holes in semiconsolidated formations, where hydraulic direct rotary drilling would be slower and down-the-hole hammer would not be suitable.

5.5.2 Rock Drilling Principles

The drillability of rocks depends mainly on the hardness of the minerals of which it is composed and the size of the grains. Quartz is one of the most common of the rock-forming minerals. Since quartz is very hard, a high quartz content (silicon dioxide content) will make the rock hard to drill and become abrasive, causing heavy wear on the drill bit. On the other hand, a rock with a large calcite content is easily drilled and causes little drill bit wear. A coarse-grained structure is easier to drill and causes less wear than a fine-grained structure. Hence, rocks with the same contents of minerals can be different in their drillability. Compressive strength of a rock is a measure of the static load a sample of rock can take until it breaks. Hence, it is often used as an indication of the drillability of a rock. A fairly good indication of the drillability of a rock can be obtained by studying its mineral composition, grain size and structure.

Rock Drilling Methods

The following are the basic methods of rock drilling:

(i) *Percussion Drilling*

It is the most common drilling method and is used in most kinds of rocks. It is done by top hammers and down-the-hole drills.

(ii) *Rotary Crushing*

The method, originally developed for oil well drilling, is being increasingly used in water well drilling in the recent years. The method at present is being used for drilling in rocks with compressive strength up to 5000 bars.

(iii) *Rotary Cutting*

It is used for drilling in soft rock formations with compressive strength up to 1500 bars.

(iv) *Rotary Abrasive Drilling*

It is used mainly in ground water prospecting when a core of rock is required for examination. The drilling is done with a diamond core bit.

In percussive crushing and cutting drilling, the rock is broken by being subjected to high pressure from buttons or inserts of cemented carbide. A state of stress is built up in the rock around the point of contact which increases with the increasing load. The material nearest to the button is crushed continuously into a fine powder and a crushed zone is formed in the vicinity of the button. Since the button is sufficiently pointed, the stress in the rock will gradually increase and cause the rock to be broken into chips. A uniform and high feed rate will cause the button to continue penetrating. If the button is blunt, more force will be required to cause penetration and breaking. Eventually, the breaking phase will stop and penetration will cease, despite the button being subjected to high loads. The bit buttons or inserts must always be reground before the penetration rate has decreased excessively.

In percussive drilling energy is transmitted from a rock drill through a drill steel and cemented carbide inserts to the rock, where it is used for crushing. In down-the-hole drilling energy is transmitted in the same way, but the piston of the hammer works directly on the drill bit. When drilling is done by rotary crushing, energy is transmitted to the bit through a pipe which is rotated and which presses the bit against the rock. The cemented carbide buttons are pressed into the rock and break off chips in the same way as in percussive drilling. In the rotary cutting method, energy is transmitted to the insert through a drill tube which rotates and which presses the inserts against the rock. The edge of the insert then generate a pressure on the rock and cracks off chips.

To enable drilling to proceed effectively, it is essential that the bottom of the hole is kept clean and the cuttings are continuously removed from the drilled hole. This is done with a flushing medium which may be air, water or foam, which is forced down to the bottom of the hole through a central flushing hole in the drill rod and flushing passages in the drill bit. The cuttings, mixed with the flushing medium, are forced out of the drill hole through the space between the rod and the wall of the drill hole. To obtain effective cleaning of the hole, the flushing air must flow at a high velocity. It is, therefore, essential to have the correct balance between the quantity of air flow and the space between the pipe and the wall of the drilled hole.

5.5.3 Types of Air-Driven Drilling Rigs

Down-the-hole drills are available for various types of uses. These include the light-duty in-well drills (Fig. 5.37), wagon drills (Fig. 5.38) and truck/tractor-mounted drills (Figs. 5.39 and 5.40) of various capacities. The drill unit can be powered by a separate prime mover or, when mounted on a truck or tractor, the power-take-off of the tractor or the truck. Tractor-mounted units are suitable for carrying over difficult terrain.

Wagon drills are equipped with two large wheels fitted to fixed axles, and a small point wheel with a draw bar (Fig. 5.38). The large wheels can be locked and anchored to the rock. The drill is equipped with a hydraulically operated boom and a high-pressure air system. It is mounted on a chain feed. The feed can be rotated through about 130º around a cross bar. The height of the drill above the ground can be varied by setting the front wheel anchor points at different angles. The chain feed and the rock drill are operated by suitable controls.

In wagon drills and in-well rigs, a portable compressor is hauled by a tractor or other vehicle while the drilling equipment is carried in a wagon. In truck-mounted units, the air compressor and rig units are mounted on a specially built platform on the chasis of a heavy-duty truck. The drilling rig comprises a mast, an air motor coupled to a speed-reduction gear box, a pneumatic feed motor, winch units, drill rods, jacks, stabilizers, and control panel. The hydraulic system comprises a hydraulic pump

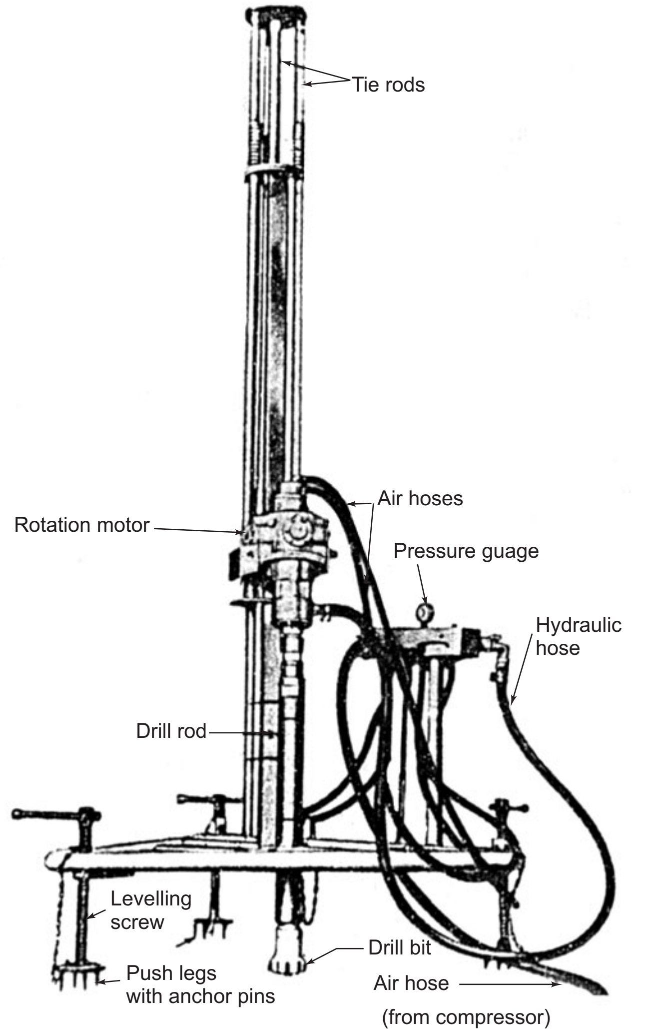

Fig. 5.37 A light-duty down-the-hole drilling equipment, popularly known as in-well rig, suitable for drilling vertical bores at the bottom of hard rock wells. The rig is suitable for drilling holes upto 45 to 50 m deep and 105 to 115 mm diameter. *Adapted from:* Water Development Society, Hyderabad (Anon., 1983a)

driven by an air-motor. Hydraulic or mechanical jacks provide proper positioning of the mast. The mast is a sturdy steel frame provided with drill guides. It is raised and lowered by a powerful hydraulic cylinder. The rotation unit is usually a multi-cylinder radial piston-type air motor directly coupled to a speed reduction gear box. The stabilizers are either mechanically operated or hydraulic powered. Drill rods are hydraulically operated. They are usually 115 mm in diameter and 4. 5 to 6 m long. The rod changer is hydraulic operated. To insert and remove the drill tubes into and out of the spindle, a hydraulically driven winch and special tube lifts are used. A built-in lubrication system provides controlled flow of the lubricating oil into the air line for positive lubrication of the air motors and the hammer.

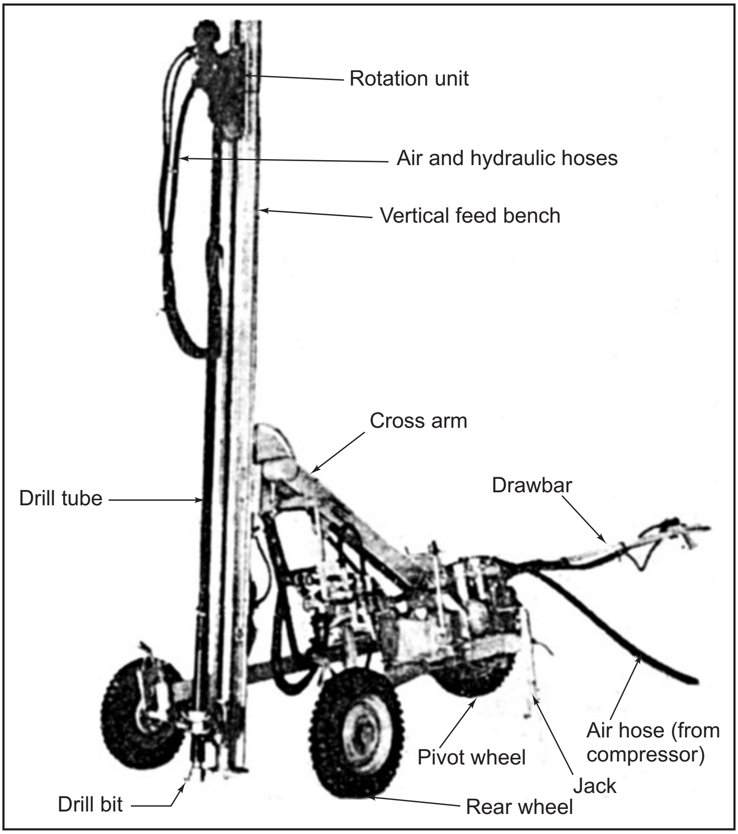

Fig. 5.38 Wagon drill for down-the-hole drilling of 105 to 115 mm diameter bores up to 75 m
Adapted from: Atlas Copco (India) Ltd., Mumbai (Anon., 1983b)

DTH drills are usually used to drill holes of size ranging from 100 to 216 mm (Fig. 5.40). Rotary air drills can be used to drill larger diameter holes (usually in the range of 250 to 310 mm). The air compressors used with DTH and air rotary drills are of capacity ranging from 15 to 22 m^3/min, at 7 to 11 kg/cm^2 pressure. Operating pressures as high as 25 kg/cm^2 are used under special circumstances.

DTH drills which are available indigenously are either of the completely hydraulic type, where compressed air is used for hammer operation only, or partially hydraulic type. In all-hydraulic drill, to maintain the required bailing velocity, a smaller compressor will be required since air is required for hammer operation only. In an air-operated drill, a higher-capacity compressor will be required. Partially hydraulic type drills use the hydraulic system for mast raising, operation of jacks, rods and the break-out system. However, the top drive head and feed are controlled through air-driven motors.

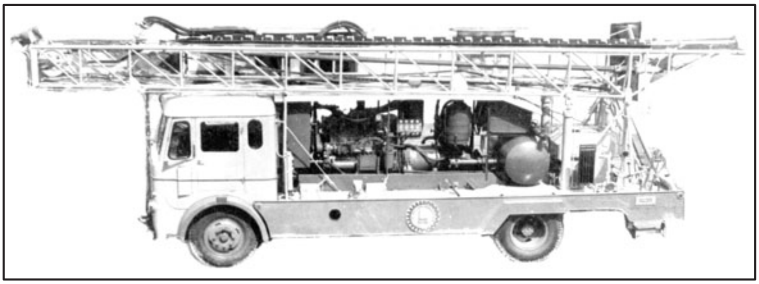

Fig. 5.39 A truck-mounted air hammer rig in transport position
Courtesy: Garlic and Co. Pvt. Ltd., Mumbai

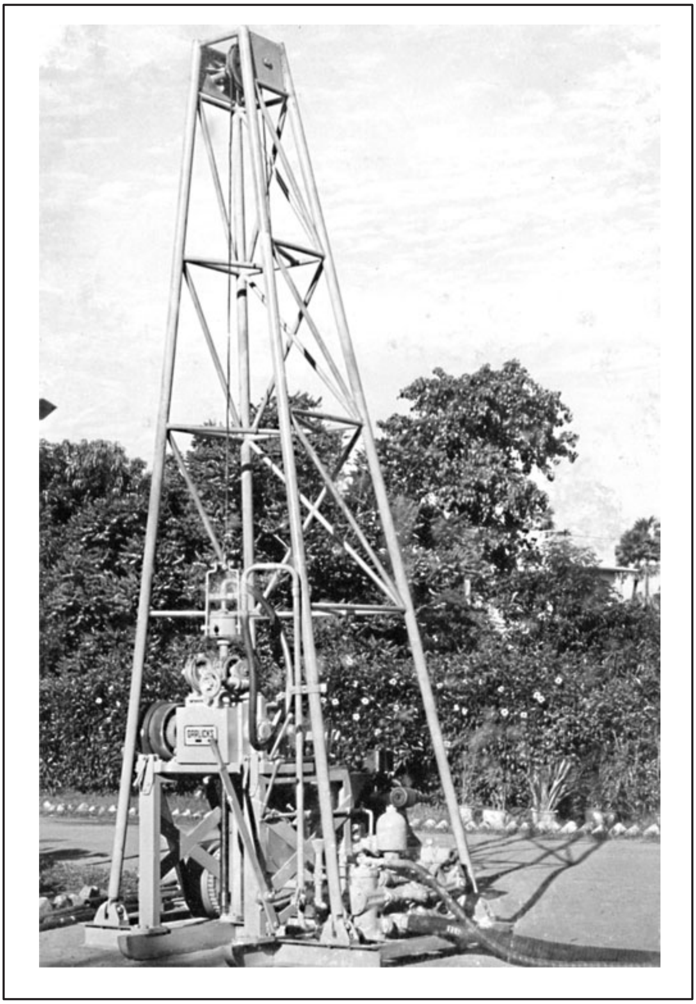

Fig. 5.40 A heavy duty rotary drill in operation
Courtesy: Garlic & Co. Ltd., Mumbai

The top drive and feed are two critical operations in DTH drilling, where hydraulic drive is more advantageous than a pneumatic drive system.

The pressure required to operate the hammer ranges between 7 and 17 kg/cm^2, and the blows per minute range from 600 to 1200. The hammer hits the bit while it is also being rotated along with the tool string. Since the hammer moves down the hole, the piston blows are transmitted directly to the bit without losing percussive energy through the drill string. Efficient cleaning of the hole is necessary so that impact is always on fresh rock.

To start drilling, air is turned on and the bit rotates and lowers slowly until it starts hammering on the formation. Initially, just enough pull-down pressure is applied to start breaking the rock. The pressure is increased gradually till smooth operation is obtained. The recommended pull-down pressure is in the range of 30 to 150 kg per cm diameter of the bit. Application of higher pressure may increase the effectiveness in hard-rock drilling. As the hole gets deeper, pull-down pressure has to be adjusted to compensate for the additional weight of drill pipes added to the drill string. With deeper holes, instead of additional pull pressure, counter-balancing of the weight of the drill string may have to be resorted to. The rotational speeds vary from 15 to 26 rpm, depending on the method of drilling. The recommended speed in DTH drilling is 15 to 20 rpm. The harder or more abrasive the rock, the lower the rate of rotation.

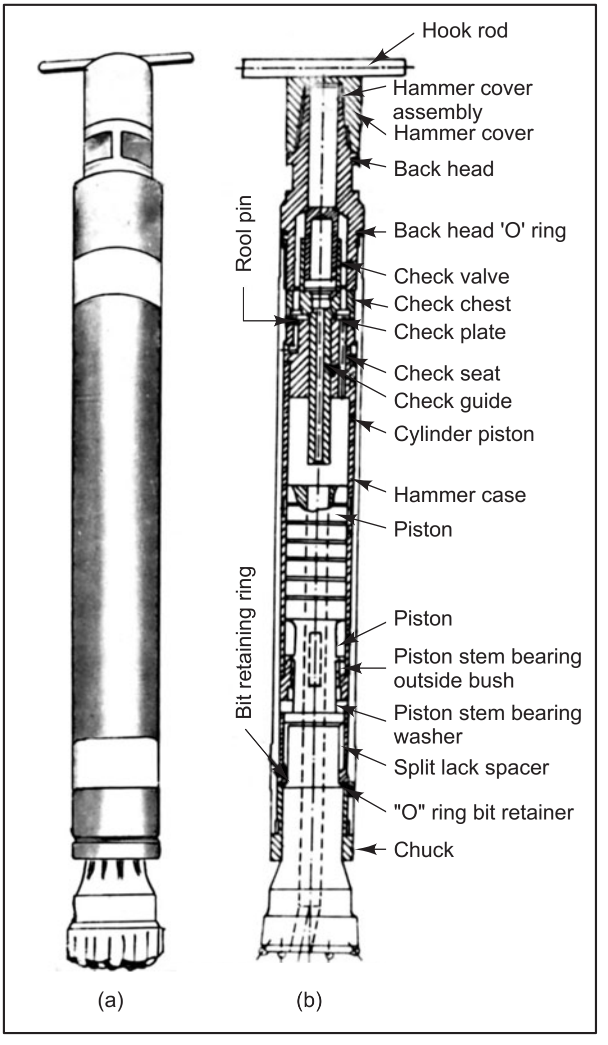

Fig. 5.41 Views of the hammer assembly of down-the-hole drill: (a) General view, (b) Sectional view showing parts
Adapted from: Krishna Rock Drills Pvt. Ltd., Secunderabad (Anon., 1983c)

Drill Hammers

The drill hammer is placed behind the drill bit (Fig. 5.41). Compressed air is used to impart percussive blows to the bit while a rotary head mounted on top of the drill string (Fig. 5.42), rotates the bit continuously through a hydraulic or air-drive motor. Drill hammers are of robust design and comprise the air piston, bit tube, valves, guides, chuck and couplings.

Feeding

The feeding mechanism varies with the type of drilling. The basic principle is that the impact energy from the drill is transmitted to the rock with a minimum of transmission loss. An essential requirement is that the bit must constantly be in contact with the bottom of the hole. In top-hammer drilling, the drill is mounted on a cradle which runs on a feed rack. Feeding can take place mechanically, utilizing a chain or screw, or hydraulically. In down-the-hole drilling, the rotation motor is located on the feed. The impact mechanism is mounted directly on the bit and accompanies it down into the hole. The feed force varies according to nature of the rock to be drilled and the weight of the drill string. It is essential that the rig is firmly erected so that the feed is secure. The feed force should be sufficient to ensure that the bit is constantly in contact with the rock. If the feed force applied is too low, it will result in poor transmission of energy. The couplings will also tend to loosen, causing excessive wear and tear. Consequently, the energy of the drill string is not transmitted to the rock, but is reflected within the drill string, giving rise to load peaks, resulting in drill steel fatigue. It also results in inefficient penetration, as the bit is not in firm contact with the rock. On the other hand, if the feed force is too high, the hammer may get stuck as a result of the reduced rotation speed. It will also result in reduced stability of the rig and vibrations, resulting in wear and tear of the equipment and crooked holes. Increased feed force will give higher penetration up to a certain extent, above which the rate of penetration will fall again.

When drilling is done by the rotary crushing method, the feed force is utilized to drive the buttons of the roller bit into the rock. In hammer drilling, however, the penetration is achieved by the shockwave. Thus, when the rotary crushing method is used, a very high feed force will be required. Harder rocks will require greater feed force. In rocks of the same hardness, increased feed force will generally improve penetration, since the buttons penetrate more deeply into the rock.

In the rotary-cutting method of drilling, the feed force has to keep the bit insert in contact with the bottom of the hole so that rock removal will take place

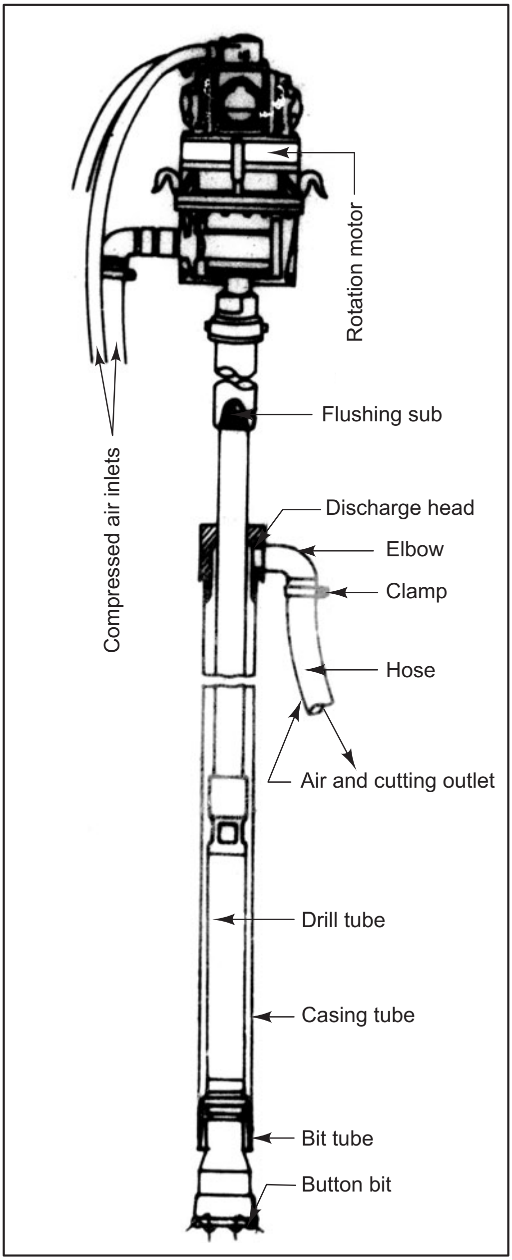

Fig. 5.42 Down-the-hole hammer drill string

continuously as the bit is rotated. Normally, increased feed force will improve the penetration rate. Field experience usually make it possible to determine the most economically advantageous feed force, giving due consideration to the penetration rate and wear on equipment.

Rotation

The drill bit is turned between succeeding blows from the impact mechanism, so that it works on a new part of the bottom of the hole. In the case of a top hammer, the rotation mechanism can either be built into the drill or incorporated in a separate rotation motor. An in-built rotation mechanism is usually built into the drill and coupled directly to the impact mechanism, so that a smaller number of blows give a slower rotation speed. If a separate rotation motor is used, the speed of rotation can be regulated independent of the impact mechanism.

In the case of a down-the-hole drill, the impact mechanism accompanies the bit down into the hole, while the rotation motor runs on the feed behind the topmost drill tube without entering the hole. The rotation between consecutive blows is adapted to produce as many cuttings as possible. The inserts or buttons must be prevented from striking the same point in the rock several times. When drilling with insert bits, a rotation speed of 80-160 rpm is usually recommended, giving a 10–20º turn between blows. For button bits, a slower rotation speed is preferred. For button bits between 51 and 89 mm diameter, a speed of 40–60 rpm is used, giving a 5–7º turn between blows. For larger bits, a slower speed of rotation is required.

In the rotary-crushing method, the bit is rotated so that a new part of the hole bottom is exposed. The rotation motor on a roller-bit rig is hydraulically powered. It is mounted at the back of the feed, on the drill string. The normal rotation speed is 50-90 rpm. In view of the variations in rock formations, the most economical speed of rotation at each individual work site is determined through field trials.

When drilling by the rotary cutting method, rock removal is accomplished as the insert is forced against the rock in the course of rotation. The rotation mechanism, which is usually hydraulically powered, is mounted on the feed at the back of the drill string. The rotation speed is normally about 80 rpm.

Hydraulic Drive System

Hydraulic drive for operating the various components of a DTH drilling unit, except the hammer, is becoming increasingly popular in the water well industry. With its inherent incompressibility, liquid is a far superior medium to transmit power, as compared to air. The components which could be operated by hydraulic drive include the top drive, feed, rod changer, auxiliary winches and water injection drive. Operations like hoisting the mast and levelling the rig can also be controlled hydraulically.

A hydraulic system transmits and controls energy or power through the use of moving and pressurised liquids within an enclosed circuit. The basic hydraulic system consists of a pump for converting mechanical energy into fluid flow for carrying the flow through (hoses/pipes) valves for controlling the pressure, direction of flow and sometimes volume, and finally hydraulic cylinders or hydraulic motors. In hydraulic cylinders and motors, hydraulic energy is converted back to mechanical energy in the form of linear or rotary motion, to do useful work such as propelling a vehicle, powering a drill or lifting a mast. The hydraulic system permits small forces to precisely control quite large ones. Its smooth motion and ability to be completely reversible are great advantages in hydrostatic transmissions. In the hydraulic system of DTH rigs, the energy is converted into rotary or linear motion to do the intended work of the system, through hydraulic motors or hydraulic cylinders.

Hydraulic Cylinders

Hydraulic cylinders transfer pressure into mechanical force. They are used where linear motion is required to move some mechanism e.g. mast raising, levelling jacks, breakout system for rods, and operating rod storage. The hydraulic cylinders are built in different sizes to fit any application.

Hydraulic Pumps

The hydraulic pump is the primary source of power from which all other hydraulic systems are operated. The three most common designs of hydraulic pumps are: (i) vane, (ii) gear, and (iii) piston types. The vane and gear designs are basically of the constant displacement type, while the piston pump is made in both constant and variable displacement types. Piston pumps are used for high pressure and have high efficiency. The length of stroke of the piston can be varied during operation, in order to obtain a variable flow. The input rating of a hydraulic pump (l/min) is related directly to its operating speed. The pressure rating of the pump is determined by its manufacturing tolerances and capabilities and has no relation to speed. The horse power required to drive a pump is dependent on both pressure and volume. The higher the pressure or greater the volume, the more the horse power required.

Hydraulic Motor

The hydraulic motor is an actuating unit providing rotary motion (e.g. top drive head in drill). In construction the hydraulic motor is similar to the hydraulic pump, but in operation it is directly opposite. Oil under pressure enters the motor causing the shaft to rotate. Unlike pumps, motors are usually reversible. The speed of a hydraulic motor is dependent upon the volume of oil supplied by the pump. The output torque of a motor is dependent on the pressure supply.

Hydraulic System Maintenance

Contamination and heat are two main causes for any hydraulic system to fail or malfunction. Contamination can come from outside (while oil changing) or from within (by wear of components). It can also be caused by particles and soluble substances produced by the chemical reaction in the system. This can be overcome by changing the filters and fluid at regular intervals as specified by the manufacturer. Regular change of filters and oil will ensure longer and trouble-free service of the hydraulic system. Heat, the other common malady, spreads damage throughout the system. Heat degrades the oil and affects the life of rubber parts like seals, rings and hoses. The major cause of heat is hydraulic fluid going from a high to a low pressure without doing work. This can be overcome at the manufacturing stage by properly designing the hydraulic system.

Drill Bits

The drill bit is the part of drilling equipment that performs the crushing work. The part of the bit which is in contact with the rock is made of cemented carbide in the form of buttons or inserts. The threaded rod of the drill string is screwed on to the bit. The impact energy is then transmitted between the end of the rod and the bit. The flushing medium is supplied through the flushing hole in the rod and is distributed through the holes in the centre and/or at the sides of the bit. The front of the bit is provided with milled grooves for flushing the cutting in the reverse direction. In order to prevent the bit jamming in the drill hole, the diameter of its front end is made larger, thus providing a clearance between the hole and the body of the bit. If the front of the bit is subjected to wear, an anti-taper is formed. Consequently, clearance is lost and the bit is likely to get stuck in the hole.

Figure 5.43 presents the common types of drill bits used in DTH and air rotary drilling.

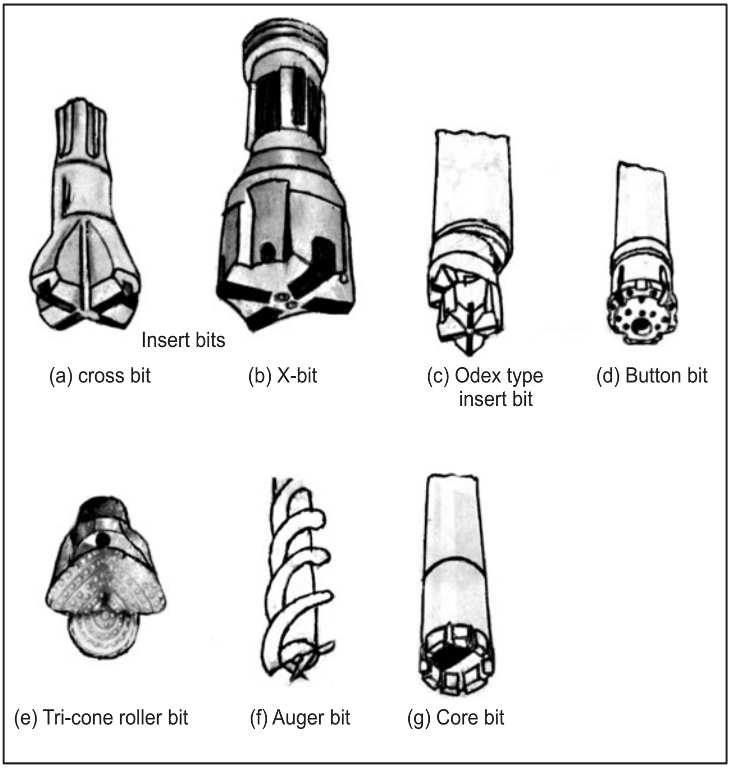

Fig. 5.43 Drill bits for down-the-hole and air rotary drilling
Courtesy: (a) and (b) Ravathi Machine Tools, Coimbatore; (c), (d), (f) and (g) Atlas Copco (India) Ltd., Mumbai; (e) Widia (India) Ltd., Bangalore (Anon., 1970, 1983b, 1983d)

Insert Bits

Insert bits are available in a variety of designs and are usually manufactured in sizes ranging from 35 to 200 mm. They have cemented carbide blade inserts brazed to the crown of the bit. The main constituents of cemented carbide are tungsten carbide and cobalt. Tungsten carbide gives the hardness/wear-resistance property, while cobalt, acting as the binding metal, gives the required toughness. The inserts may be in cross and X-designs. Cross-bits have an angle of 90º between the inserts. They are commonly used on sizes up to 57 mm. Since they are symmetrical, they are the easiest shape to grind while reconditioning the bit. X-bits have angles of 75º and 105º, respectively between the inserts. They are commonly used for large diameters (> 64 mm) and to ensure round holes. Heavy-duty bits have bigger inserts than ordinary bits. They are used in abrasive rocks producing heavy wear. Insert bits are commonly used in drilling in loose rock, filling material and soft formations like limestone.

Button Bits

Button bits (Figs. 5.44 and 5.45) provide higher wear resistance for drilling in hard formations and are popular in drilling different types of rock formations. In button bits, round carbide inserts of high hardness and wear resistance are used to perform the crushing operation. The button inserts are shrunk-fitted on to the bit-crown. Button bits often give long service and higher penetration rates than insert bits.

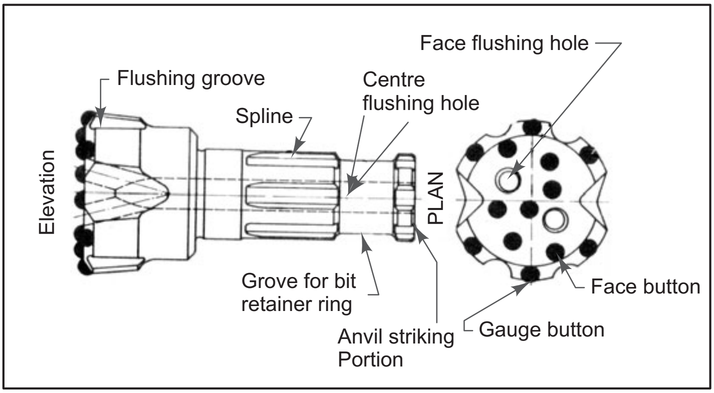

Fig. 5.44 View of DTH button bit
Courtesy: Widia (India) Ltd., Bangalore (Anon., 1983d)

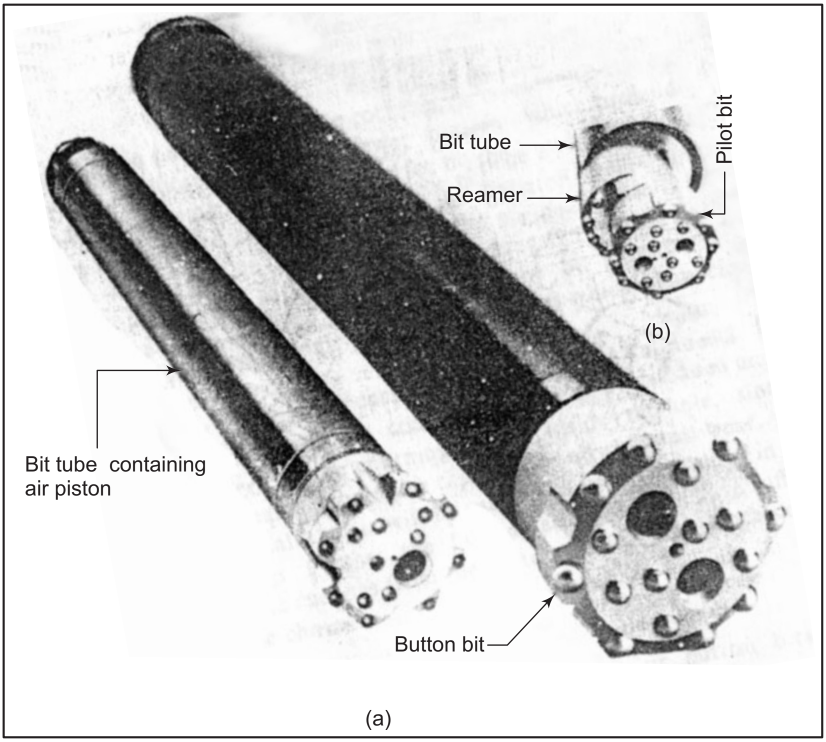

Fig. 5.45 Drill hammers containing pneumatic pistons equipped with button bits: (a) Regular, (b) ODEX type
Courtesy: Atlas Copco (India) Ltd., Mumbai (1983b)

Drag Bits

Drag bits are used when drilling is done by the rotary-cutting method. Their cutting parts are made of cemented carbide. The bit is mounted on a bit adapter and can be combined with one or more reamers.

When the inserts are worn to the extent that the clearance becomes too small, they must be reground to their original shape.

Roller Bits

Roller bits are used for drilling by rotary crushing (Fig. 5.46 to 5.48). Originally, they were used in the oil well industry. They are becoming increasingly popular in water well drilling in hard rocks, especially to construct deep bore wells. A roller bit, also called a tri-cone bit, consists of a bit body with three movable conical rollers equipped with cemented carbide buttons. The bearing system provided in the pin and cone (Fig. 5.48) of each bit leg houses one cone. The outer shells of the cones are deeply carburised and fitted with high-grade button inserts. The button profile as well as grade will vary, depending upon the strata to be drilled. In order to clear the cuttings which are formed during drilling, jet nozzles are fitted at selected places (Fig. 5.47). The buttons are distributed over the rollers in such a manner that the entire bottom of the hole is worked when the bit is rotated.

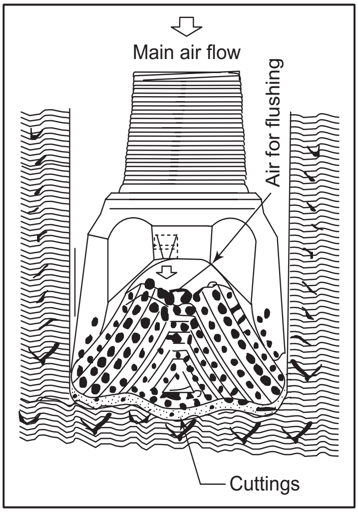

Fig. 5.46 Schematic sketch illustrating the operation of a pneumatic rock roller bit *Adapted from:* Rajamani and Chaudhary (1983)

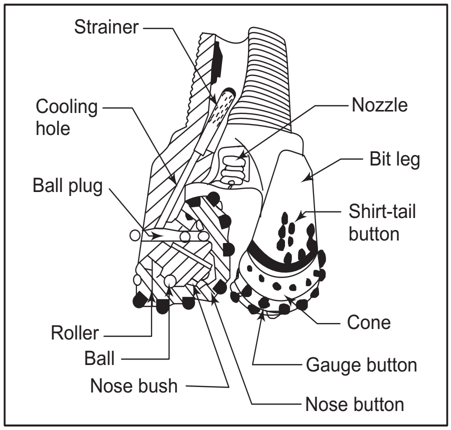

Fig. 5.47 Partially exposed view of a rock roller button bit *Adapted from:* Rajamani and Chaudhary (1983)

In drilling with roller bits, rock fracture is achieved by the pressure and torque applied through the bit to the rock. The compressed air passing through the bit nozzles clears the cuttings. The cuttings, during the process of clearing from the bottom of the hole, rub against the shirt-tail portion of the bit leg.

For drilling in hard and abrasive rocks, the buttons are closely spaced, whereas bits for looser rocks have fewer buttons which protrude farther. The grade of the cemented carbide used for making the button can be varied according to the properties of the rock to be drilled. The shirt-tail portion of the bit, which plays an important role in the bit life, is usually strengthened by putting tungsten carbide buttons and tungsten carbide hard-facing alloy to increase the bit life. The bearings in the bit require continuous cooling. This is achieved by air passages with filters which allow clean air into the bearings.

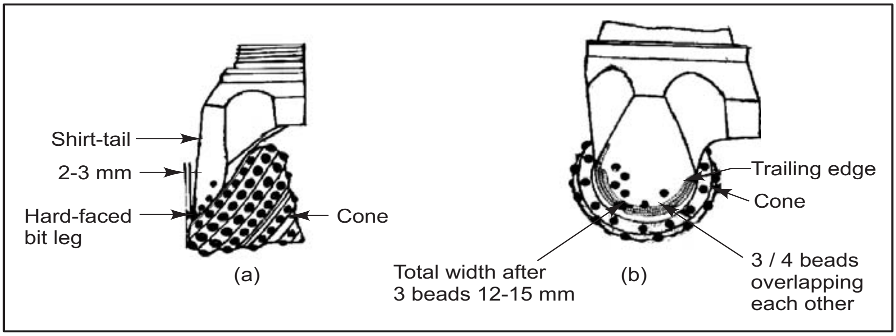

Fig. 5.48 Hard-faced rock roller bit: (a) Hard-faced bit leg and cone showing the clearance required between cutting section of cone and bit leg, (b) Deposition of metal on a worn bit leg by arc welding. Note the deposition from trailing edge closely overlapping the previous bead and maintaining same bead thickness
Adapted from: Anon. (1983d)

It is important to choose the correct nozzle size for air flushing. If the nozzle size is too small, the air compressor will be over-loaded and will stop frequently. There will be churning action inside the hole, since the cuttings are not cleared, leading to rapid cone and shirt-tail wear. If the nozzle size is too big, all the air will be used for flushing, resulting in overheating of the bearings. Further, the flushing air will not have sufficient velocity to pick up the cuttings from the bottom of the hole. Hence, correct nozzle size has to be chosen.

ODEX Type Bits

ODEX bits, used in DTH drilling, may be insert bits or button bits. The ODEX bit consists of three parts, namely, pilot bit, reamer and guide (Fig. 5.49). The reamer turns eccentrically about the shaft of the pilot bit. The ODEX method of well drilling is based on the principle of under-reaming. The eccentric bit makes it possible to insert casing tubes into a hole at the same time as the hole is being drilled. During drilling, the reamer on the ODEX bit swings out and drills a hole larger than the outer diameter of the casing tube. When the desired depth has been reached, the ODEX bit can be lifted through the casing tubes, which remain in the hole. Rock drilling can then continue with the standard equipment, namely the conventional DTH or rotary bits. The ODEX method is useful when the wall of the drilled hole is unstable.

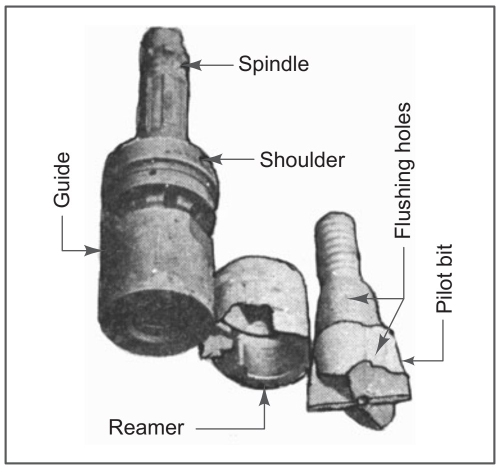

Fig. 5.49 Component parts of an ODEX drag bit
Courtesy: Atlas Copco (India) Ltd., Mumbai (Anon, 1983b)

Auger Bits

Auger bits are used for initial drilling through the overburden (soil column lying above the rock layers). It is useful in clay formations which stand without caving.

Core Bits

Core bits have relatively short inserts which leave an uncrushed core of rock in the centre.

Drill Bit Maintenance

The following maintenance procedures ensure efficient and trouble free service of DTH hammer bits:

1. *Positioning*. Stability of drilling rig is to be ensured by firm support to get vibration-free drilling.
2. *Correct fitting of bit in hammer*. The hammer bit after proper cleaning, should be fitted using proper sized parts like split ring, holding pin and chuck. This ensures the transmission of energy along the axis of piston without undue losses and without any unwanted stresses being developed in the bit.
3. *Collaring*. Collaring involves the alignment of the bit coaxial with the hammer.
4. *Drilling*. For the optimum utilization of kinetic energy of piston for breaking the rock, the three main parameters of drilling, namely, feed, rotation and flushing are important.
   (a) *Feed*. It is the firm contact of bit with rock. This is necessary for maximum utilization of energy in breaking the rock. Too high feed leads to vibrations. It may also damage the carbide inserts. Too low feed would make the joints of drill string loose and the popping off of the inserts.
   (b) *Rotation*. For the optimum breaking of rocks, appropriate speed of rotation is necessary to provide suitable angle of turn between the two blows of the hammer. Depending on the type of rock, the speed of rotation can be regulated.
   (c) *Flushing*. Adequate flushing is necessary to evacuate the rock cuttings so that a fresh surface of the rock is exposed to the bit.
5. The bit after use should be reground at proper intervals.
6. Avoid idle hammering i.e. ensure proper rotation while the drill-rod is being operated.
7. Store the drill bits in wooden boxes to avoid damages to buttons.
8. While coupling and breaking the bit from the hammer, extra care is to be taken to avoid carbide buttons hitting the steel portions of the bits in the box.
9. To ensure efficient performance, two or three bits are often used in a cycle for the completion of a bore. It should be ensured that the diameter of the bit which is used is smaller than the one which was removed.
10. In the process of drilling, jerkey rotation, besides a drop in penetration rate, would sometime be due to loss or chipping off of a button. If this is noticed, it is advisable to withdraw the bit immediately for check-ing and servicing.

Regrinding and Rebuilding of Roller Bits

Bit dressing is an important factor to increase bit life and improve the performance of DTH and air rotary drill bits.

Insert bits. The tungsten carbide inserts wear due to continuous use. Different rocks show different wear patterns and when the specified wear limit is reached, it is necessary to grind the inserts as per manufacturer's specifications. The tungsten carbide tips are ground and checked with template for their shape and size.

Button bits. In case of button bits, regrinding of the buttons to their original hemispherical shape ensures faster penetration and longer bit life. Regrinding becomes necessary when the rate of penetration reduces. The hemispherical shape of the gauge button of a DTH button bit can be checked with a bit gauge (Fig. 5.50). As a general rule it can be said that if the rate of penetration falls to about half the normal rate, the formation being the same, the bit needs regrinding. As compared to the insert bits, the interval between two regrinds in case of a button bit is longer. However, timely withdrawal and regrinding will save the bit and also increase its working life. The wear of a button bit is characterized by flattening of the side and the face of the gauge buttons. The "flat wear" can be checked with the button gauge.

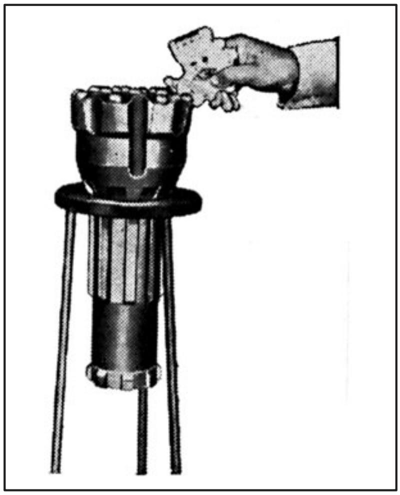

Fig. 5.50 Checking the hemispherical shape of the gauge button of a DTH button bit with a bit gauge. Note that the hammer bit is held in a stand for regrinding
Courtesy: Widia (India) Ltd., Bangalore (Anon., 1983d)

Regrinding procedure. Regrinding is done by a pneumatically operated die grinder. The spindle speed of the grinder is between 20,000 to 25,000 rpm. Properly dressed silicon carbide mounted point grinding wheels are used for grinding the buttons. Both cylindrical and conical grinding wheels are used in bit dressing. Wet grinding is preferable to dry grinding. In case of DTH bits the drill bit should be placed on a bit grinding stand and secured firmly to avoid chattering. A copious supply of the coolant should be constantly directed towards the button being ground. While grinding the buttons, care is taken so that the grinding wheel is not put on a particular point of the carbide for a long time. This will lead to over-heating and cracking of the carbide.

Roller bits. The wearing point in a roller bit is usually the shirt-tail. The process of shirt-tail wear becomes prominent as the depth drilled increases. At the final stage, the hard facing provided to protect the shirt-tail starts wearing off as well as peeling off. If the bit is allowed to drill further, the edge of the shirt-tail portion of the leg disintegrates and the rollers get exposed, which, in turn, leads to the rapid failure of the bit. After each bore is completed, bits are to be inspected for shirt-tail wear.

Hard facing procedure. The hard facing surface is to be cleaned thoroughly. If a major portion of the previously hard faced material is worn out and only a small portion is left clinging to the shirt-tail, the same should be removed by grounding. A water tub is used for hard facing of rock bits. The cone, including bearing assembly is fully immersed in water where a portion of the shirt-tail is exposed to the atmosphere. The operator positions himself to face the cone and starts welding at the trailing edge of the bit and the welding is continued to the leading edge of the shirt-tail. After each bead of hard facing, sufficient time is given to cool the hard faced portion before sprinkling water. This will prevent the hard faced portion from cracking. A bead width of 5-6 mm and a thickness of 2-3 mm along the lower edge of the shirt-tail is preferred. Deposition is to be done close to the end of the shirt-tail. The thickness of deposition should not exceed 2-3 mm. In a similar manner, starting from the trailing edge and closely overlapping the previous bead, another layer of hard facing is done, maintaining same bead thickness. The procedure is to be repeated till a good shape of deposition is achieved.

Hard faced portion is closely examined for any visible cracks. The gap between gauge button of the cone and the bit leg after deposition should be in the range of 2-3 mm. If this is less, the hard faced portion is carefully ground off, otherwise deposit starts peeling off.

5.5.4 Drilling with Foam

Foam, as a flushing medium has been found to be advantageous in hard-rock drilling, in difficult terrain with loose sands, cobbles and boulders. The foam helps lift the cuttings and also has a lubricating and stabilising effect on the walls of the hole. A foam flushing unit used for this purpose is shown in Fig. 5.51.

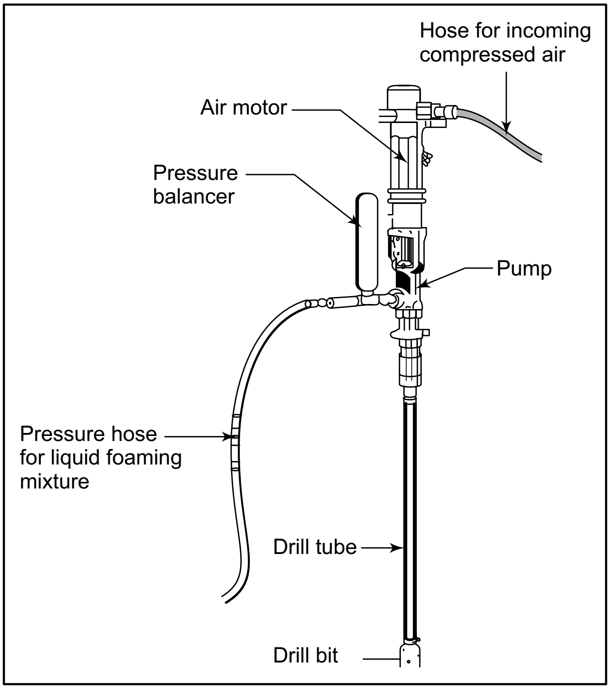

Fig. 5.51 Feed motor of hammer drill equipped with foam flushing unit
Courtesy: Atlas Copco (India) Ltd., Mumbai (Anon., 1983b)

The material used for foam-flush drilling is a concentrated foaming agent with good emulsion and foam stability. The injection process forms small, tight, thin walled bubbles which give a cutting carrying capacity far in excess of the conventional water-based muds. With very low hydrostatic head, good bottom hole cleaning is provided. This gives substantial increase in the penetration rate and in bit life.

The addition of HEC (hydroxyethyl cellulose) based polymers or other additives, such as high-yield bentonite, will give a stable foam which increases the bubble strength, thereby increasing the lifting capacity of the foam column. The use of additives to the foam can stabilize swelling and sloughing in shales by limiting the loss of fluid into the formation. It will also reduce the tendency towards balling up of clays.

To begin foam-flush drilling in a dry hole, a mixture of 1 per cent foamer (by volume) in water is recommended. Foamer in small amounts can be added, as required, to increase the density. The drilling of loose formations will require a mixture of 3 to 5 per cent of foamer.

Control of the foam column is important. Adjustments to air and foam injection must be made as necessary to achieve the desired foam column. A steady flow of air at the surface indicates that a column is not forming. The flow of air can be decreased or the foam injection increased, until a gentle surging of the column is obtained. Excessive air will channel through the foam and destroy the cutting-carrying capacity and mud collars, and erosion will occur. The foam should flow in a gentle, surging action from the bore. Penetration rates must not exceed the carrying capacity of the foam.

5.5.5 Drilling Through Overburden

In water well drilling in hard rock areas, drilling through overburden to reach bed rock is often a difficult part of the operation. For such formations, where DTH rigs are used, the overburden is drilled through with a DTH hammer and an oversize bit, or with a roller bit if the rig is hydraulically powered. Such an operation will be successful if the hole remains open till the hard rock is reached and is then cased before proceeding further.

Overburden consisting of boulders, sand and gravel often cannot be drilled by conventional methods, since the hole tends to collapse before it can be cased. The ODEX method is suitable for drilling through difficult and collapsible overburdens. The method is based on a pilot bit with an eccentric reamer, which drills a hole slightly larger than the external diameter of the casing. The casing tube follows the reamer down into the hole, as it is being drilled. It does not rotate but is driven smoothly down by the feed force or by the impact of the DTH hammers.

On completion of drilling, the ODEX equipment is put into reverse rotation and the reamer automatically swings inwards, allowing the whole unit to be retracted back through the casing. Once solid bedrock has been reached, further drilling is carried out with standard drilling equipment.

5.5.6 Air Compressors

Air compressors used in water well drilling may be mounted with the drilling rig or towed separately (Fig. 5.52). The compressors are of the single-acting, two-stage design with two or four cylinders usually in a 'V' arrangement, inter-cooler and pump lubrication. They have a dry intake-air filter. Efficient filter action reduces wear on the compressor and hence, maintenance costs. The prime mover is a diesel engine equipped with a speed regulator, cooling fan, oil and air filters, and a generator for charging the batteries. The compressor cylinders and inter-cooler are cooled by a fan fitted to the compressor shaft. The engine has a cooling-air fan mounted on a chasis with torsion bar suspension and two pneumatic-tyred wheels. The tubular frame also serves as an air receiver. The drawbar on the unit incorporate a towing eye and a retractable front support pivot wheel.

5.6 MISCELLANEOUS DRILLING METHODS

The basic drilling methods, namely percussion, hydraulic rotary and down-the-hole and air rotary systems, have been described in preceding sections. In addition, there are drilling applications requiring distinctly different drilling equipment to suit specific site requirements and/or economy. They include core drilling, calyx drilling, jetting and sonic drilling.

5.6.1 Core Drilling

The main objective of core drilling is to obtain uncontaminated samples of underground formations, for various purposes like soil sampling, geological and mining investigations, ground water prospecting and foundation engineering. Diamond core drills are usually used for soil and rock sampling and in the planning and checking of civil engineering works. They are also employed for the drilling of blasting holes and for grout injection.

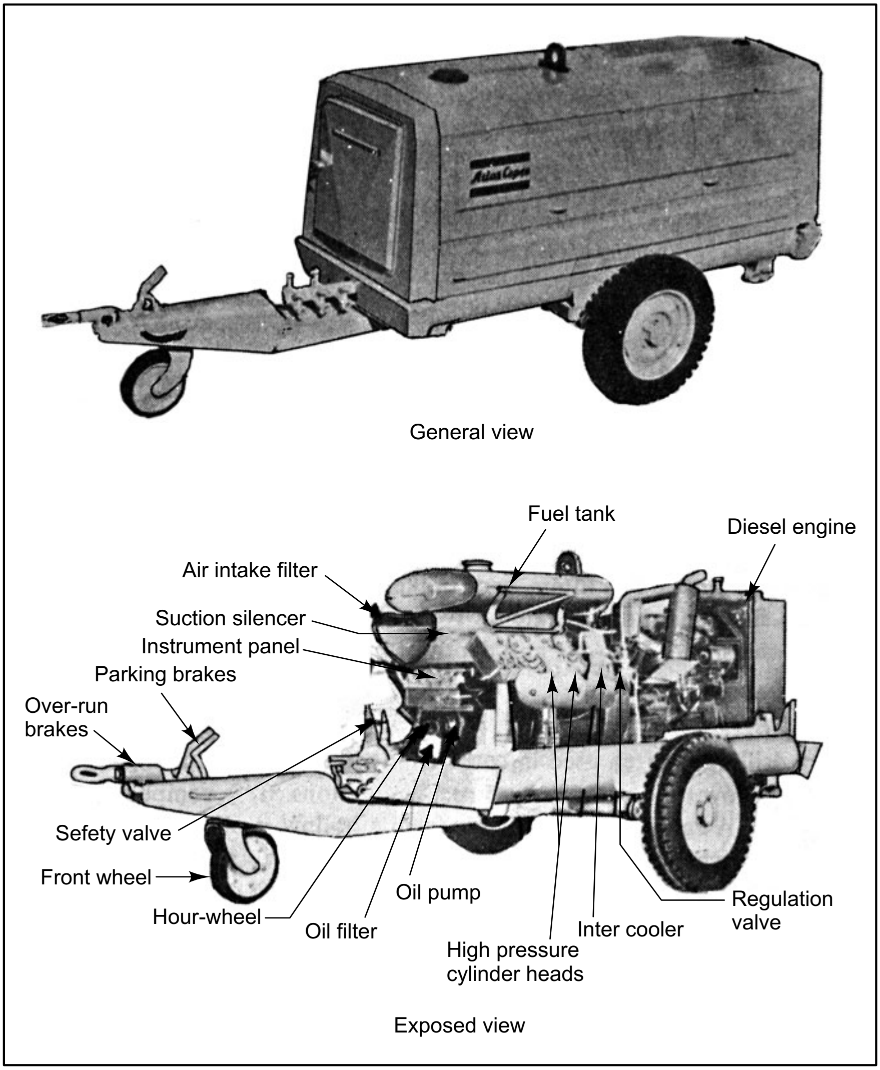

Fig. 5.52 Portable piston type air compressor commonly used to operate air percussion drills and allied compressed air tools. The capacity of such compressors usually range from about 5 to 10 m^3/min. at 7 kg/cm^2. *Adapted from:* Atlas Copco (India) Ltd., Mumbai (Anon., 1983b)

Diamond core drills are equipped with core bits. They are commercially available for drilling cores for shallow, medium and deep bores. They may be powered by either electric motor, air motor, or diesel engine and are equipped with either hydraulic or pneumatic rod extractor, gear box and controls. A derrick is used to withdraw and insert the drill string with a conventional core drill. The masts are mounted directly on the machine. A one-leg derrick can be used with rods up to 6 metres long, while a tripod derrick can handle rods up to 9 metres.

There is a large array of tools and accessories to facilitate rod handling, such as automatic rod lifters, rod brakes, rod holders, hoisting swivels, blocks, safety hooks and water swivels, all of which are available in sizes to suit the size of the rods and depth of the hole.

5.6.2 Calyx Drilling

Calyx drilling is often used in core drilling and for constructing large diameter shallow tube wells in hard rock formations. It is comparatively less expensive. A calyx drill bit is made from a hollow steel tube with two inclined slots which is connected below another tube (core barrel), which is further connected to the drill rods. These are rotated mechanically. Chilled shots are fed to the bottom of the bit through the drill string along with water. These are ground by the shot bit to form abrasive material with sharp edges which cuts into the consolidated formation, forming an annular ring to form a core inside the core barrel. The core barrel is taken out from the well by grouting the core with quartz chips.

5.6.3 Jetting

The jetting method of well construction is limited mainly to alluvial formations under shallow water table conditions. In India, the method is common in West Bengal and Orissa. Jetting is convenient for boring through hard and tenacious clays in which the progress of boring with ordinary percussion rigs is usually very slow. In a jetted well, a drill bit with nozzles is attached to the drill pipes at its bottom. Water is pumped at high pressure through the bit. The drill rods are rotated manually. The hole is drilled by the force of a high velocity stream of water. The stream loosens the material as it strikes and washes the finer particles and carries them upward and out of the hole. The technique of constructing a jetted well may be varied according to the kind of equipment available.

Jetting Equipment

The essential jetting equipment (Fig. 5.53) includes a hoist, jetting bits, a jetting pump, water swivel, drive weight, a set of heavy duty pipe tools and an adequate supply of drilling fluid.

Hoist

A hoist is required to handle the drill pipe and casing. An ordinary tripod with pulley block may be used.

Bits

Various types of bits are employed in jetting (Fig. 5.54). In soft materials, an expansion-type bit may be used to make a hole slightly larger than the casing. When using a hand rig, hard layers of formation are penetrated by the percussion method, using a straight bit. With heavier rigs, one of the drill-like bits can be used to penetrate hard layers that do not yield to the water jet.

Pump

A pump with suitable hose connection, capable of delivering 250-500 1/min at a pressure of 3.5 kg/cm^2, is adequate in jetting. The quantity of water required to jet a well varies with the type of material being penetrated. Sandy soils require large quantities of water, but high pressure is not necessary. About 3 kg/cm^2 nozzle pressure at the bit is adequate in most cases. Clay and hard pans require less water but are not readily displaced, except by a small cutting stream delivered at high pressure.

Swivel

The water swivel must be able to carry the weight of the drill pipe and sustain the maximum pressure delivered by the pump.

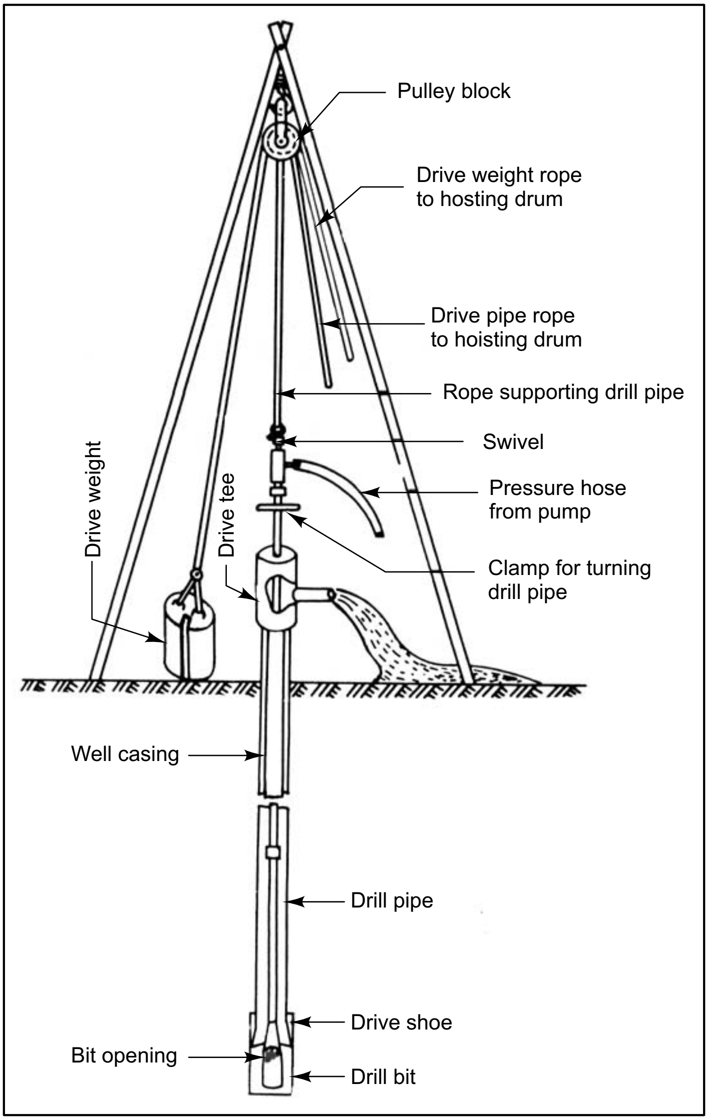

Fig. 5.53 A simple jetting rig

Adapted from: U.S. Dept. of Army and Air Force Tech. Manual (Anon., 1957)

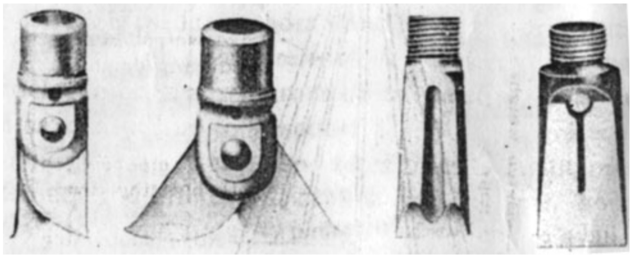

Fig. 5.54 Commonly used types of drill bits for jetting equipment
Adapted from: U.S. Dept. of Army and Air Force Tech. Manual (Anon., 1957)

Jetting Fluid

Plain water is commonly used in jetting wells. However, a jetting fluid of greater viscosity and weight may be prepared by mixing clay or commercial bentonite with water. This heavy fluid tends to seal the wall of the hole and prevent loss of water into the formation being penetrated. In addition, it prevents the hole from caving when sand formations are encountered. At the ground surface, jetting fluid is led from the hole to a settling pit, where the cuttings settle to the bottom. The fluid can be picked up again by the jetting pump and recirculated.

Setting Casings and Well Screens

When the jetting fluid effectively prevents caving or collapse of the drilled hole, the casing can be inserted in a single operation after jetting has been carried to the full depth. Otherwise, the casing is sunk as fast as jetting proceeds. If too much resistance is encountered, a certain amount of driving is required to force the casing down. The well screen is installed by lowering it through the casing to the bottom of the well. The casing is then pulled back to expose the screen to the water bearing sand.

5.6.4 Sonic Drilling

Sonic drilling is used for continuous sampling and well installation in unconsolidated and soft fractured bed rocks. The primary benefits of this method are that very rapid drilling rates are possible combined with reduced volumes of secondary waste.

A sonic drill rig looks and operates very much like any conventional top-drive rotary or auger rig. The main difference is that a sonic drilling rig has a specially designed hydraulically powered drill head or oscillator which generates adjustable high frequency vibrational sinusoidal forces (generally between 50 and 120 cycles per second). The sonic head is attached directly to the core barrel, drill pipe or outer casing, sending the high frequency vibrations down through the drill steel to the face of the drill bit creating the displacement, fracturing or shearing action depending upon the formation being drilled.

The oscillator uses two eccentric, counter rotating balance weights or rollers that are timed to direct 100 per cent of the vibration at 0 degrees and 180 degrees. There is an air spring system in the drill head that insulates or separates the vibration from the drill rig itself. This principle is shown in Fig. 5.55.

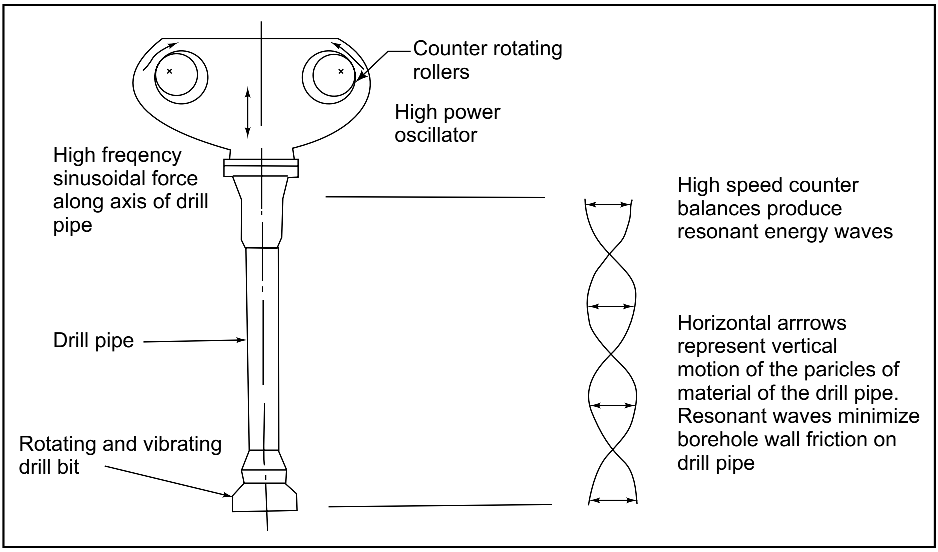

Fig. 5.55 Basic principle of sonic drilling

The vibrational frequency is controlled to suit operating conditions and to achieve optimum drilling rates. When the vibrations coincide with the natural resonate frequency of the steel drill rod or casing, a natural phenomenon called resonance occurs, therefore the word resonants. Resonance allows the rig to transfer timed vibrational energy into the top of the drill string, utilizing the natural stored energy of the steel, to cause the drill string to act like a flywheel or a spring delivering tremendous amounts of energy directly to the bit face. This, plus the fact that the soil particles along the side of the drill string tend to fluidize or move away from the drill string allows for very fast penetration rates. In many overburden formations, a sonic drill rig can achieve rates of 30 cm per second.

The basic components of a sonic drilling rig are shown in Fig. 5.56.

A sonic drill rig advances a 7.5 cm to 25 cm diameter (nominal) core barrel for sampling and can advance up to a 30 cm diameter outer casing for the construction of standard and telescoped monitoring and recovery wells. When drilling, the core barrel is advanced ahead of the outer casing in 30 cm to 10 m increments, depending on the type of material, degree of subsurface contamination and sampling objectives.

The outer casing can be advanced down over the inner drill rods and core barrel, or after the core barrel has moved ahead to collect the undisturbed core sample and has been pulled out of the borehole. The outer casing can be advanced completely dry in most situations, or it can be advanced with water or air or a drilling fluid with additives depending upon the formations being drilled, the depth and diameter of the borehole, or requirements of the project.

The sonic system can be used for almost any type of drilling. At this time, the system is most effective for depths to 150 m depending upon conditions. The sonic rig utilizing air or wireline tools is capable of drilling much deeper. Today sonic drill rigs are primarily utilized for environmental drilling. Some mineral exploration, construction drilling, angle drilling, deep geotechnical, water supply wells, and numerous other types of drilling are also being done.

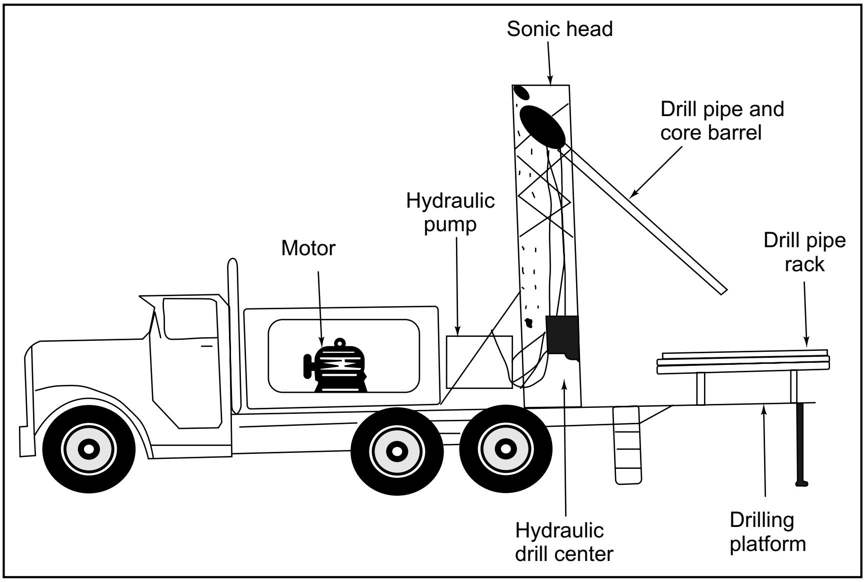

Fig. 5.56 Sonic drilling

5.7 CHOICE OF DRILLING METHOD

India is a vast country, with a diversified hydrogeological setting. The geological formations in the country may be broadly classified as alluvial, semi-consolidated and consolidated. Alluvial formations, comprising about 30 per cent of the total land area of the country, are relatively rich in ground water resources. Ground water in such formations can be tapped by various types of rotary and percussion rigs, including hand-boring sets. Semi-consolidated formations comprise only about 5 per cent of the total land area. Consolidated formations (hard rocks), comprising crystalline rocks, granites, gneisses, schists and basalts, cover about 65 per cent of the total land area. Air-operated down-the-hole rigs have proved to be the best for fast construction of water wells in these areas. In specific areas, such as '*tarai*' and '*bhabar*' belts, comprising sand-gravel-boulder beds with clays, combination rigs (percussion and rotary) have proved to be effective in constructing tube wells.

Adaptability of Different Drilling Methods

The method of drilling a tube well would depend mainly on the lithology of the area where the well is to be constructed, the type of water bearing formations to be encountered, diameter and depth of the well, the availability of water for drilling, approachability to the drilling site and economic considerations. Table 5.2 shows relative performance of different drilling methods in various types of geologic formations.

Percussion Drills

Between the two basic techniques of drilling, namely, percussion and rotary, by far the greater number of wells in India are drilled by the cable tool percussion method. Percussion drilling is a satisfactory method of boring in almost all types of formations (with some exceptions), if speed is not a serious consideration and the size and depth of the bore are not very large. The cost per metre of drilling is lower for relatively shallow holes in unconsolidated materials. A percussion drill is lighter and can be easily transported in over rough country.

TABLE 5.2 Relative Performance of Different Drilling Methods in Various Types of Geologic Formations

Type of formation	Cable tool	Direct rotary	Air rotary	Reverse rotary	Air operated down-the-hole hammer	Dual-wall reverse rotary	Jetting
Loose sand and gravel	2	5	+	5	+	6	1
Loose boulders in alluvial fans	3	2	+	2	+	4	1
Clay and silt	3	5	+	5	+	5	3
Sandstone	3	3	5	3	+	5	+
Limestone	5	5	5	5	6	5	+
Basalts	3	3	4	3	5	4	+
Granite	3	3	5	3	5	4	+
Metamorphic rocks	3	3	4	3	5	4	+

+ Not recommended
Rate of penetration:

1. Impossible
2. Difficult
3. Slow
4. Medium
5. Fast
6. Very fast

In certain types of formations, such as dune sand, quicksand and unconsolidated river gravel cable tools are unsatisfactory and at times unusable, particularly for drilling deep, small-diameter wells. The pounding of the drill, the low fluid level, and the lack of mud sealing contribute to slumping and caving in such formations.

The percussion method requires much less drilling water than the rotary method. It is, therefore, more suitable for boring in areas where sufficient water is not available within a reasonable distance. Under the drilling technique adopted in the percussion method, a more accurate sample of the formation is obtained than in the rotary method. In percussion drilling, it is possible to test the quantity and quality of water in each stratum as the drilling proceeds and zones of poor quality water can often be shut off by leaving a blank casing through the contaminated stratum. Such information is difficult to obtain in case of the rotary method due to the mixing of dislodged soil material and drilling mud.

A percussion rig is suitable for boring in dug wells, as it can be conveniently installed on the side of the well (hand-boring sets can be installed over the well) and carry out boring in the centre.

Rotary Drills

For drilling large holes, particularly where speed is an important factor, rotary drilling is most suitable. The conventional direct rotary drill is specially adapted to drilling the pilot bore for exploration and then reaming to a bigger size when the production well is to be constructed. With this system, drilling can be carried down as deep as 1000 m or more.

For drilling in lowlands with clay, silt or sticky shale formations, and saline or alkaline conditions, the rotary rig is a much faster method. Dunes, wind blown sand and quicksand are handled easily by rotary machines. However, rotary drills are unsatisfactory in extremely permeable lost-circulation zones. The circulating fluid is lost to a large extent in such formation and drilling, at times, becomes extremely difficult. The rotary method may not drill successfully in alluvial formations with boulder beds and cobbles as well. The removal of large cobbles with circulating mud fluid becomes difficult. The cost of drilling large diameter holes by the rotary method usually does not go up in the same proportion as in cable tool work. This means that where favourable conditions exist, large diameter holes can be drilled more economically by the rotary method.

Reverse Rotary Drilling

This method is gaining popularity because it is economical and adapted to alluvium, specially when the depth is limited to about 300 m. Older models of the rigs were capable of drilling to a maximum depth of about 200 m. With the introduction of force pumps, jet educators and air-injection systems in modern designs of reverse rotary rigs, wells of depth up to 300 m are possible.

A study conducted by Trimmer *et al*. (2003) on the clogging of conventional wells that pump anaerobic ground water from an aquifer composed of sandy, fluvial sediments shows that the clogging rate for 15 wells drilled using the cable tool technique is significantly lower than for 7 wells drilled using the reverse rotary technique.

The study reveals that the actual drilling technique has an influence on well performance and clogging rates. Less clogging was observed during the first seven years when cable tool drilling was used. In seven years, the specific capacity drops to a 40 per cent level (average use 80 m^3/h, 12 hours a day, 365 days a year). After reaching 40 per cent of the initial specific capacity, these wells need rehabilitation every 2-3 years. Conversely, in the first seven years, the reverse circulation drilled wells needed rehabilitation every 2 years. On the one hand, cable tool drilled wells therefore saved the cost of two rehabilitations compared to the reverse circulation rotary drilled wells. On the other hand, cable tool drilling is considerably more expensive than reverse circulation rotary drilling. Therefore reverse circulation rotary drilling could be economically justified even if more maintenance would be needed. Cable tool drilling would be preferred from a technical viewpoint, whilst from an economic viewpoint reverse-circulation rotary drilling may be preferred.

Down-the-Hole Drilling

The down-the-hole drill is advantageous for drilling small diameter wells in hard rock formations. When water is to be obtained from crevices of weathered rock or hard rocks, this process is used to flush away the cuttings, drill open bores in rocks as hard as granite and tap water from an open bore.

Direct-cum-Down-the-Hole Hammer Method

When the hard rock is below an over-burden (soil and subsoil layer) of 10 to 30 m, this method is used. The initial over-burden is drilled by the direct rotary system. The down-the-hole hammer is used for drilling in hard rock. The over-burden layer is encased.

Miscellaneous Drilling Methods

Among the other methods of drilling, the auger method has a specific limited use for boring shallow wells in unconsolidated formations which can normally stand without casing. Core drilling is a suitable method only where it is necessary that the soil sample should be extracted in the form of a core, for investigation purposes. The method is very expensive for water well drilling. Jet drilling, common in Bengal and Orissa, is limited to constructing shallow tube wells in loose sandy formations. Calyx drilling is successful for shallow tube wells of large diameter in consolidated formations.

Certain areas, like the '*bhabar*' and '*tarai*' belt and the foothills of the Himalayas, are covered with boundary formations associated with sedimentary formations and clay belts, and are tackled by combination-type rigs. The boulder formation is drilled by the percussion method, and the rest of the formation by the rotary method. The rig, thus, independently performs percussion drilling and rotary drilling according to need.

5.8 INSTALLATION OF WELL SCREENS AND CHECKING WELL ALIGNMENT

The well screen is the most important component of a tube well drilled in sand and gravel formations. Its correct installation and proper alignment are important aspects of well construction. The well screen supports the formation, prevents caving and permits water to enter the well easily through closely spaced openings. The screens are made with openings of various sizes to fit the gradation of the water-bearing sand. The procedure for the installation of well screens depend on the method of well drilling and the type of well, i.e. strainer well or gravel-packed well. Taking accurate measurements of pipe length, screen length, cable length and depth of hole are fundamental requirements in well screen installation.

5.8.1 Installation of Well Screens in Strainer Type Wells

After drilling is complete, if the well is to be developed as a strainer well, strainers have to be located against the water-bearing strata to be tapped and plain pipes against the remaining strata. Strainers and plain pipes are arranged at the ground surface in the same order as they are to be lowered into the bore and are serially numbered. At the bottom end of the tube well, it is advisable to keep a small length of plain pipe (about 1.5 m long) with a cap to close the end. This cap is known as a bail plug and has an 'eye' in it. It is useful in extracting the strainers, if necessary, by lowering a hook (Fig. 5.57) to contact the 'eye' and pulling the whole strainer assembly up. The plain pipe at the bottom provides space for the settlement of heavy

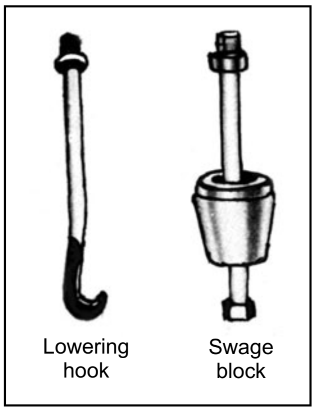

Fig. 5.57 Well screen tools

particles which get into the well during its development. This will prevent the bottom end of the strainer getting choked, which would otherwise restrict the flow in a useful portion of the aquifer.

The technique for installing well screen depends on the method of drilling. In case of strainer wells, percussion drilling is usually used (Fig. 5.58). Shallow wells in alluvial formations are usually drilled by hand boring. In this case, strainers and plain pipes are lowered inside the bore, one by one, as required, starting from the bottom end, and in the same order in which they have been arranged at the ground surface. This is done by fixing a pair of clamps to the top of the end piece and lowering it inside the bore till it rests on the clamp on top of the outer casing pipe. The next piece is then screwed on top of the bottom piece and a second set of clamps is fixed at the top end of the upper piece. The upper clamp is tied to the wire rope around the pulley at the apex of the boring tripod. The other end of the rope is coiled round a crab winch. The rope is tightened till it takes the whole weight of the pipes to which the clamp is fitted and raises these by a few centimetres. This lifts the lower clamp from the top of the boring tube and enables it to be released. The lower clamps are then removed, the wire rope gradually slackened and the assembly lowered into the bore till the upper clamp rests on top of the outer casing pipe. The wire rope is then removed and the next pipe screwed on top of the previously lowered pipe and the whole operation repeated as before. Thus, one by one the whole series of pipes and strainers is lowered inside the bore hole to the correct level.

Fig. 5.58 Lowering a well screen into the casing pipe of well drilled with a percussion drilling rig

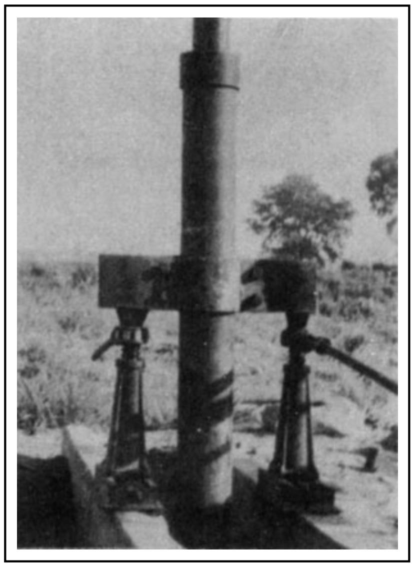

Fig. 5.59 Taking out the outer casing pipes by manually operated jacks

The whole length of pipes and strainers is kept suspended from the top, while the outer casing pipes are jacked up (Fig. 5.59) and extracted one by one. As the boring pipes are extracted, the earth and sand surrounding them get loosened, grip the strainers and pipes on the outside and help hold them in position.

If the drilling has been done by the standard cable tool method, the casing may be pulled by jarring with the drilling tools. The drilling cable is used for lowering the strainers and pipes into the well bore. Either mechanical or hydraulic jacks may be used to provide the necessary lifting force. A pulling ring or spider with wedges or slips may be used to grip the casing. Sometimes, the boring pipe can be pulled with the casing line on the cable tool drilling machine.

5.8.2 Installation of Well Screens in Gravel Pack Wells

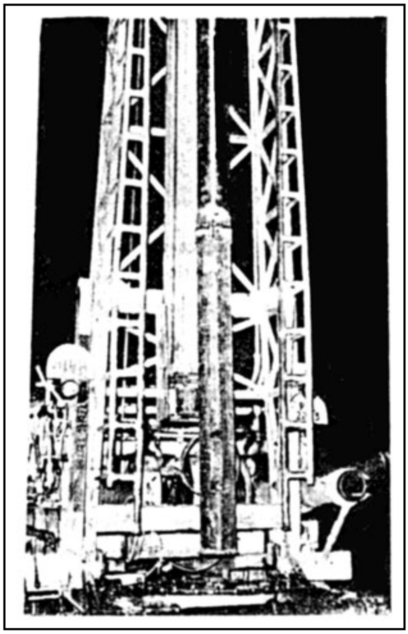

Fig. 5.60 Lowering of well screen and casing pipes in a bore drilled with a reverse rotary drilling rig

The well screens used in gravel pack wells are slotted pipes. The method of installing the slotted pipe depends upon the method of drilling. When the drilling has been done with a percussion rig, before lowering the strainers and pipes, the casing may be pulled up to the proposed bottom level of the tube well assembly and the bore hole filled with sand or gravel up to this height. This will enable the tube well assembly to rest on a sand or gravel base. Gravel is poured from the top in the annular space between the well pipe and the casing. Initially, a length of about 3 m above the top of the slotted pipe is filled with gravel. The casing pipe is then lifted about 10 cm from the bottom and water is pumped out from the well till it becomes clear.

Back-Blowing, i.e. blowing air into the well to dislodge the sand particles clogging the gravel, should be done with the help of an air compressor. The process of lifting the casing pipe, pumping water till it becomes clear and back-blowing till the casing tube is extracted upto a metre above the top of the slotted pipe, are continued. During the entire operation, gravel is fed continuously into the annular space to maintain its level about 3 m above the top of the well screen. While the process of development and gravel pouring continues, the casing pipe is gradually withdrawn by means of jacks. Extraction of the casing pipe should be slow, in order to ensure that the well screen is not dragged up with the boring pipe. It is of great importance that the strainer assembly should be at the centre of the boring pipe.

When a gravel-packed well is constructed with a rotary rig, the drilled hole should be washed clean of cuttings and finally reconditioned with fresh drill fluid of good viscosity before lowering the strainer and pipe assembly. The hole should be kept full of drilling fluid during the lowering of pipes so that it does not cave-in. The slotted-pipe strainers and plain pipes are lowered one by one in the bore, as required, starting from the bottom end. The bottom end is provided with a bail plug, as described earlier. Guides, with outer diameters equal to the diameter of the bore, are fixed to the tube well assembly at suitable intervals, in order that it will be centered at all points in the bore (Fig. 4.20). After lowering, the assembly should be suspended to ensure its precise centering in the hole. A reducer is provided to join the housing pipe with the casing (Fig. 4.1).

Before feeding the gravel, water is introduced into the system and the mud weight in the annular space reduced substantially. Gravel is then introduced at the surface against the circulating stream, or pumped through a tubing into the annular space. The circulating stream serves to remove fine materials from the gravel and prevents possible bridging. During the introduction of the gravel pack, the top of the well assembly is sealed so that the circulating water returns through the annular space. In the construction of a gravel-packed well by the reverse rotary method, the well assembly is held in tension and guided for centering in the hole. The hole is kept full of water while lowering the assembly and gravel is fed into the annular space from the surface or pumped through a pipe.

5.8.3 Plumbness and Alignment of Tube Wells

In spite of exercising reasonable care in boring, the finished well sometimes get slightly out of plumb. That is why the inside diameter of the housing pipe in a tube well is always kept larger than the outside diameter of the pump bowls. So long as the eccentricity of the well does not exceed the clearance allowed in this gap, there is no problem with the well.

Often, when the eccentricity is not within permissible limits, the tube well cannot be operated with a vertical turbine pump, since misalignment would cause severe wear on the pump shaft, bearings and discharge casing. In severe cases, it may be impossible to get a pump installed. However, if an air lift pump or a volute centrifugal pump is to be used, alignment is not so important. But air lift pumps are inefficient and volute centrifugal pumps have only a very limited suction lift to pump a deep tube well effectively. Submersible pumps also can tolerate slight misalignment. It is suggested, however, that even if the intention is to install a type of pump that will tolerate misalignment, the requirement of tolerable limits of verticality should be enforced.

Normally, tube wells are tested for verticality after drilling is complete and the well assembly lowered. However, in case of gravel-packed wells, the verticality is checked immediately after gravel packing has been done up to the reducer joining the housing pipe with the lower smaller diameter section.

Verticality Test

A simple method of measuring eccentricity in a bore is by use of a heavy plumb-ring, 6 mm smaller in diameter than the inside diameter of the well casing. The plumb-ring is suspended by means of a thin strong wire of steel or copper running over a pulley, rigidly fixed to the apex of a tripod (Fig. 5.61). The tripod pulley is at least 3 m above the top of the casing. The tripod is so adjusted that the wire passes through the centre of the top of the well casing. The plumb-ring is lowered in steps of 3 m and the deviations of the line from the centre of the casing are observed (Fig. 5.62). The drift at any depth is given by the deviation multiplied by the length of the line and divided by the height of the pulley above the top of the well casing.

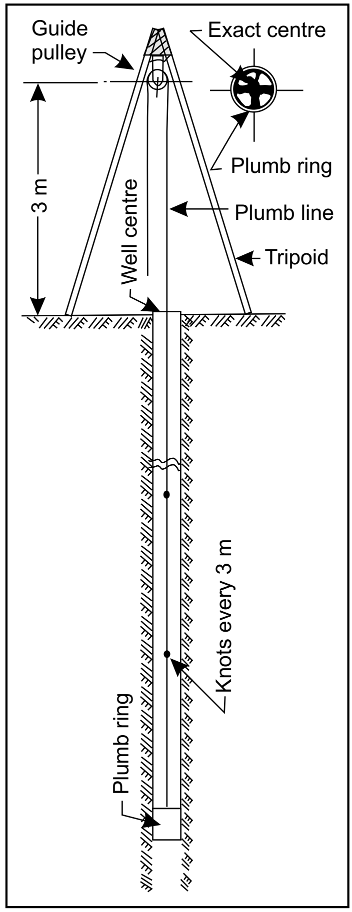

Fig. 5.61 Verticality test of tube well

Example 5.1 The deviation, measured from the centre of the casing at the top of a well, is 2 mm when the plumb-ring is lowered in the bore by 3 m. The pulley of the tripod is 4 m above the top of the well. Determine the drift in the well casing at a depth of 3 m.

Solution

The drift at any depth is given by the deviation multiplied by the length of the line and divided by the height of the pulley above the top of the well casing.

Length of the line = 4 + 3 = 7 m

Height of the pulley = 4 m

Deviation at the top of the well = 2 mm

$$\therefore \quad \text{Drift at a depth of 3 m} = \frac{2 \times 7}{4} = 3.5 \text{ mm}$$

Fig. 5.62 Measurement of deviation of plumb line from the centre of a tube well at its top

In case of a slanting bore, the eccentricity may be in one direction only. However, in case of crooked well, it could be in different directions. Therefore, along with the measurement of eccentricity, the direction should also be recorded. A plot of the eccentricity measurements with respect to the depth will help determine the clearance available for the pump to be lowered into the well.

In case the eccentricity of a bore is more than permissible limits, it can be corrected by loosening earth on one side of the pipe and forcing the pipe back by applying jacks on the other side (Fig. 5.63).

Fig. 5.63 Procedure for straightening a tube well. Note the plumb line, cross wires and jacks

5.9 SEALING OF BRACKISH AND SALINE AQUIFER HORIZONS

Brackish and saline water occurring in some aquifer horizons may sometimes be a serious problem in well construction. Techniques are available to 'seal' these horizons, once they are properly identified.

5.9.1 Procedure for Sealing Saline Aquifer Zones

The individual aquifers are tested separately by the drill stem test, so that one aquifer does not contaminate the water of the other. A packer is used to isolate one from the other. The test is carried out from the top zone towards the bottom, one after the other. The pilot hole is reamed, with a bit of the same size as of the packer, to a firm strata, such as clay, above the aquifer, and the packer is lowered to rest there. Slotted pipes are placed opposite the aquifer and the water pumped by an air-lift pump. The drilling fluid is maintained above the packer to avoid the risk of collapse of the hole. This process is repeated for every aquifer, one after the other. Water samples from each aquifer are collected and analysed for quality.

Sealing Saline Top Zones

In some cases, the top horizons may have saline water while water of good quality exists in the lower horizons. To seal such zones, the well pipe assembly is lowered in such a way that the blank pipe is placed opposite the saline aquifer. The well is gravel-packed upto a few metres below the saline aquifer, where there is an impervious strata at least 6 metres below the saline aquifer. Cement slurry is pumped into the annular space between the casing and the well bore and around the casing pipe, in order to fill up the space (Fig. 5.64). Slurry is usually prepared by mixing 3 kg of bentonite and 25 l of water with 50 kg of cement (one bag). The slurry is allowed to settle there for at least 72 hours. Thus, the upper aquifer is sealed off from the remaining bottom aquifers and cannot contaminate the water below. The annular space over the cement plug can be filled with clay.

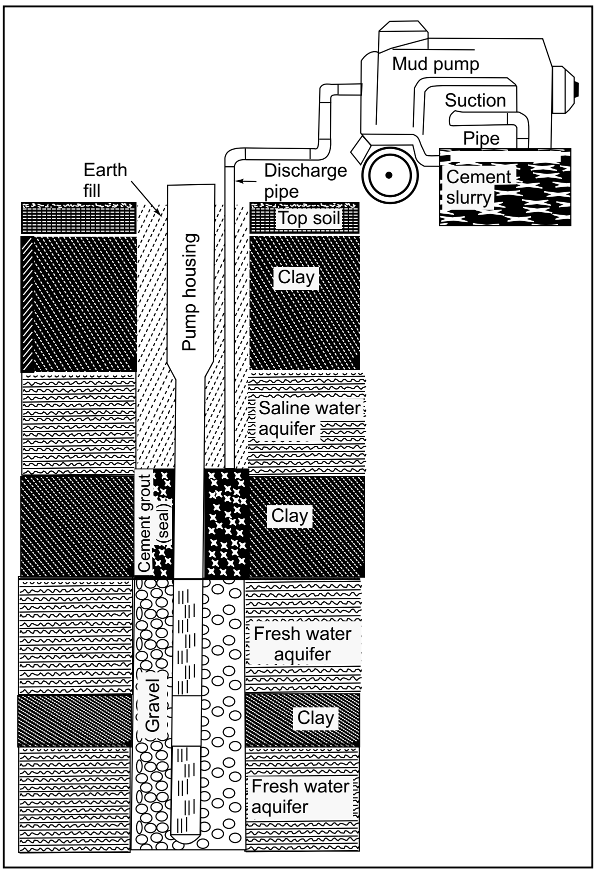

Fig. 5.64 Sealing of top saline zone in a tube well

Sealing of Intermediate Saline Aquifers

Sometimes, intermediate aquifers are observed to be saline and have to be sealed off from top zone as well as from the bottom aquifers. This is a somewhat complicated job and requires considerable precaution and care. To seal the saline zone, the assembly of pipes is lowered as usual, taking care that the saline

aquifers are faced against blank pipes (Fig. 5.65). The well is gravel-packed up to a few metre below the saline aquifer. It is essential to ensure that proper gravel packing is done up to such a point.
This may be possible only by surging the well against the lower aquifer in order to get the gravel settled properly. After a proper gravel pack is ensured, cement slurry is pumped at the top of the gravel pack and below the saline zone. If the saline layer is not very thick, the slurry may be pumped up to the top of the saline aquifer so that the entire aquifer is sealed off. In case the aquifer is very thick, sealing has to be done at the bottom of the aquifer and at its top, and clay and other material may be filled in between the two sealing layers. The cement slurry is allowed to remain for about 72 hours. Gravel packing is again done above the top cement seal for the upper aquifers. The same process can be repeated if there is more than one saline aquifer.

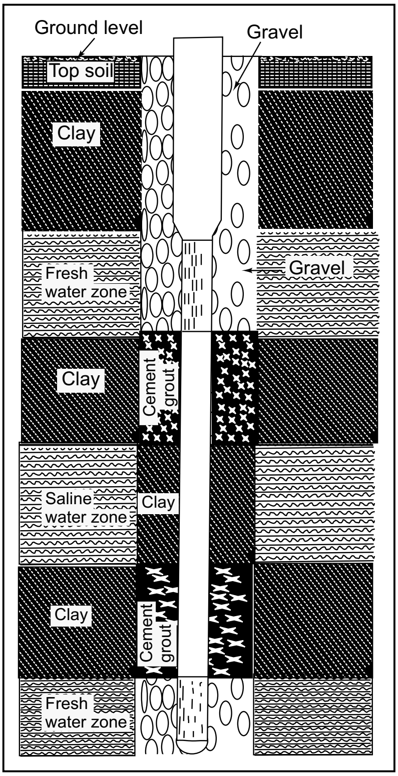

Fig. 5.65 Sealing of intermediate saline zone in a tube well by concrete grouting

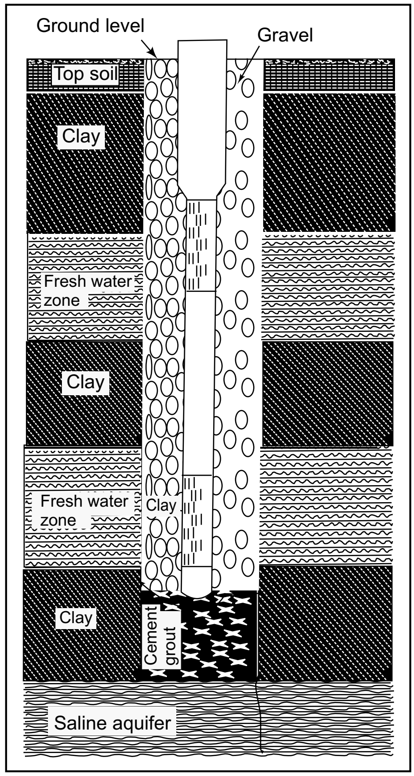

Fig. 5.66 Sealing of bottom saline zone in a tube well by concrete grouting

Sealing the Bottom Zones

There are cases where only the bottom zones are saline. In such cases, the sealing is easy and may be done with or without cement. In most of cases, saline aquifers can be ignored and only the top aquifers, which are suitable can be tapped (Fig. 5.66).

The consistency of the cement slurry requires special attention. It is necessary to estimate the drilling fluid pressure at the various depths where cement slurry has to be pumped, and the density of the slurry has to be the same as that of the drilling mud. In order to have the desired density of the slurry, various additives are used. These include gel, hydrocarbons, barite, calcium chloride and sodium chloride.

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SHORT QUESTIONS

I. State True (T) or False (F).

1. Driven well is constructed with a high velocity jet of water.
2. Driven wells are of small diameter.
3. The continuous-slot well point has a screen with a vertical openings.
4. In driving method, well pipe is always kept full of water.
5. Percussion and rotary methods of well drilling are commonly used in hard rock areas.
6. The down-the-role drilling methods combines the rotary action of rotary drilling and vibrating action of sonic drilling.
7. No fluid is circulated in cable tool drilling method.
8. Percussion drilling is better than rotary drilling in rocky formations.
9. Cable tool drilling and percussion method of drilling can be used synonymously.
10. Sand reel and drilling reel refer to the same item.
11. Drilling reel is used for operating boring pipes tools.
12. In hard limestone formations, the most important function of the drill bit is penetration.
13. The capacity of the percussion rig depends upon the weight of the drill bit.
14. Flat-flutted drill bit is used for drilling in hard formations.
15. A bailer is provided with a flap valve at the top and a cutter shoe at the bottom.
16. A sand pump is equipped with a dart valve.
17. The casing pipes are used in percussion method of drilling.
18. Sand blowing and quicksand during boring refer to the same phenomenon.
19. Reverse rotary drilling rig is equipped with a mud pump.
20. The kelly helps in rotating the string of tools and drill rods.
21. In reverse rotary, the bore hole is prevented from caving by the hydrostatic pressure of water in the bore hole.

22. The development of a tube well drilled by reverse rotary method is bit difficult because of formation of a filter cake.
23. The cable tool drilling method is the preferred method of well drilling while rotary and reverse rotary drilling are considered to be outdated drilling methods.
24. In direct circulation hydraulic rotary drilling, the drilling fluid is pumped down through the drill pipe.
25. The direct rotary drilling rig is equipped with a centrifugal type mud pump.
26. The fish-tail drag bit is a two way bit.
27. In drag bits the drilling is done by shearing and scraping action.
28. Roller type bits are suitable to drilling into hard formation.
29. The kelly in a rotary drilling rig is mostly circular in section.
30. In direct rotary drilling, the drilling fluid return to the surface through the annular space between drill pipe and bore hole.
31. Biodegradable drilling fluids cause less clogging than non-degradable fluids.
32. Bentonite is an example of biodegradable drilling fluid.
33. Gelling is a property of drilling fluid.
34. Drilling fluid create a thin film of small particles on the hole to prevent caving.
35. Drilling fluid viscosity is primarily a measure of its ability to carry cuttings down the hole.
36. Muddy water can also function as the drilling fluid in direct rotary drilling.
37. The formation of filter cake cannot avoid loss of fluid into permeable formations.
38. The porosity of the formation material determines the viscosity of drilling fluid.
39. The maximum desired limit of sand content in drilling fluid is 2 per cent.
40. In lost-circulation zone the consumption of drilling fluid decreases.
41. Accurate strata sampling is easy in direct rotary drilling method.
42. The 'gunk squeeze' is a method of sealing zone of lost circulation.
43. In reverse rotary drilling clear water is used as drilling fluid.
44. In reverse rotary drilling the drilling fluid is fed down the drill pipe.
45. The drill pipe bore hole in reverse rotary drilling is cased during drilling.
46. The drill pipes used in reverse rotary drilling are small in diameter in comparison to direct rotary drilling method.
47. The reverse rotary drill and direct rotary drill works on the same principle.
48. A centrifugal pump is used to remove the cuttings in reverse rotary drilling method.
49. A non-clog impeller is provided in the centrifugal pump used for pumping drilling fluid.
50. During drilling by reverse rotary method, the fluid level in the bore-hole is always kept at ground level all times.
51. The strata sampling in reverse rotary is much faster than other methods of drilling.
52. The rate of drilling in reverse rotary drilling is much faster than other methods of drilling.
53. Reverse rotary drilling is suitable for drilling in areas with inadequate water supply.
54. Reverse rotary drilling is one of the most economical methods of drilling.
55. Compressed air can be used in rotary drilling rig for drilling to deeper depths.
56. In dual-wall reverse circulation rotary method, the inner pipe acts as casing and outer casing rotates, acting as drill pipe.
57. Air-operated down-the-hole (DTH) drills are more effective in hard rock areas.
58. Air rotary drilling is limited to consolidated materials.
59. Button bits are less wear resistance.

60. Roller bit is also called a tri-cone bit.
61. Calyx drilling is suitable for constructing large diameter shallow tube wells in hard rock areas.
62. In jetting method of well construction the hole is drilled by force of a velocity of compressed air.
63. Sonic drilling is not suitable for continuous sampling.
64. In sonic drilling it is possible to achieve very fast penetration rates.
65. Core drilling is most suitable to obtain uncontaminated samples of formation material.
66. Diamond core drills are used for ground water sampling.
67. The greater number of wells in India are drilled by cable tool percussion method.
68. Direct rotary drill is adapted to drilling the pilot bore for exploration.
69. The cost of drilling large diameter holes by the rotary method usually go up in the same proportion as in cable tool method.
70. In case of strainer wells, percussion drilling is usually used.
71. Before feeding the gravel, water is introduced into the annular space between casing pipe and well bore.
72. Verticality test measures the depth of bore.
73. In slanting bore, the eccentricity could be in different directions.
74. In case of crooked well, the eccentricity may be in one direction.
75. Drill stem test is used to test individual aquifer.

Ans. True 2, 4, 7, 8, 9, 12, 13, 17, 18, 20, 21, 24, 26, 27, 28, 30, 31, 33, 34, 36, 38, 39, 42, 43, 47, 48, 49, 50, 52, 54, 55, 57, 58, 60, 61, 64, 65, 67, 68, 70, 71, 75.

II. Select the correct answer.

1. For drilling of large diameter bore at a faster rate in alluvial formation, the most suitable drilling method is
   (a) direct rotary (b) reverse rotary
   (c) cable tool percussion (d) jetting
2. For drilling of bore in rock, medium hard, soft and boulder formation, the most suitable drilling method is
   (a) direct rotary (b) reverse rotary
   (c) jetting (d) cable tool percussion
3. Rolling-cutter type bits are also called
   (a) drag bits (b) percussion drill bits
   (c) fish tail bits (d) rock bits
4. The reverse rotary method is not suitable for drilling in
   (a) alluvium (b) sandstone
   (c) silty clay (d) shale formation
5. The capacity of a cable tool rig is a function of
   (a) the diameter of the hole (b) the depth of the hole
   (c) the total weight of the drill string plus the cable
   (d) the size of the cable
6. Cooling, clearing and stabilizing describe the functions of
   (a) drill bit (b) drilling fluids
   (c) drill pipe (d) drill rig
7. The best method for construction of water wells in hard rock area is
   (a) cable tool percussion (b) direct rotary
   (c) air operated down the hole (d) reverse rotary

8. Accurate strata sampling is possible in which drilling method?
   (a) air rotary (b) direct rotary
   (c) reverse rotary (d) cable tool method
9. In which type of drill higher capacity air compressor will be required?
   (a) all hydraulic (b) air operated
   (c) partially hydraulic` (d) percussion
10. The recommended speed in DTH drilling is
   (a) 15-20 rpm (b) 25-30 rpm
   (c) 35-40 rpm (d) 45-50 rpm
11. In rotary crushing method, the bit is rotated at a speed of
   (a) 20-40 rpm (b) 40-60 rpm
   (c) 50-90 rpm (d) 90-160 rpm
12. Which drilling method is used to obtain uncontaminated samples of underground formations?
   (a) core (b) jetting
   (c) rotary (d) DTH
13. In jetting, adequate nozzle pressure is
   (a) 1.5 kg/cm^2 (b) 3 kg/cm^2
   (c) 5 kg/cm^2 (d) 7 kg/cm^2
14. The best drilling method for fast construction of water wells in consolidated formation is
   (a) air operated DTH (b) cable tool percussion
   (c) rotary (d) calyx
15. The economical method of drilling in alluvium formation is
   (a) direct rotary (b) reverse rotary
   (c) cable tool (d) DTH
16. Marsh funnels is used to measure
   (a) density (b) viscosity
   (c) sand content (d) filter cake
17. The maximum desired limit of sand content in bentonite based drilling fluid is
   (a) 2 per cent (b) 5 per cent
   (c) 7 per cent (d) 9 per cent
18. Drilling fluid back flow is caused by
   (a) drill bit jamming (b) lost circulation
   (c) falling soil particles (d) junk squeeze
19. The primary advantage of the dual-wall reverse circulation method is
   (a) continuous sampling of strata (b) suitability for drilling in hard rock area
   (c) suitability for drilling large diameter well
   (d) suitability for drilling in stiff clay or shale formation
20. In pneumatic direct rotary drilling method, the circulatory medium is
   (a) water (b) compressed air
   (c) mixture of water and compressed air (d) drilling fluid

Ans. 1 (b) 2 (d) 3 (d) 4 (d) 5 (c) 6 (b) 7 (c) 8 (a)
9 (b) 10 (a) 11 (c) 12 (a) 13 (b) 14 (a) 15 (b) 16 (b)
17 (a) 18 (c) 19 (a) 20 (c)

6

Development and Testing of Tube Wells

The development of a tube well is essential to obtain an efficient and long lasting well. Following the development of a new well, it is tested to determine its yield and drawdown.

Development of a tube well involves removal of finer material from around the well screen, thereby enlarging the passages in the water bearing formation to facilitate entry of water. Development increases the effective radius of the well and, consequently, its yield.

6.1 OBJECTIVES OF WELL DEVELOPMENT

The following are the main objectives of well development:

1. *To correct any clogging of the water bearing formation.* Every method of well drilling clogs the pores of the water-bearing formation around the drilled hole, to a greater or a lesser extent. In the direct rotary method of well drilling, the mud fluid results in a mud cake formation around the walls of the drilled hole. In the cable tool method of well drilling, the driving of the casing pipe results in vibrations around the pipe, which compacts the granular material of the aquifer and thus reduces its porosity. Similarly, in reverse circulation drilling, though no drilling mud is used, some silt, clay and fine sand particles are picked up from the formations penetrated during the drilling operation. These fine materials, when recirculated, get deposited on the wall of the bore hole. They should be removed to ensure proper yield of the well.
2. *To increase the porosity and permeability of the water bearing formation in the vicinity of the well.*
3. *To stabilize the formations around the well screen so that the well will yield sand-free water.* In the process of development in a zone just outside the well screen, all particles smaller than the screen opening are removed, leaving only the coarser material in place. A little farther away, some medium-sized grains remain mixed with the coarse particles. Beyond this zone, the material gradually grades back to the original character of the formation (Fig. 6.1). This stabilizes the formation so that sand-free water is pumped out at optimum capacity.
4. *To removes organic and inorganic material which may inhibit effective well disinfection.*

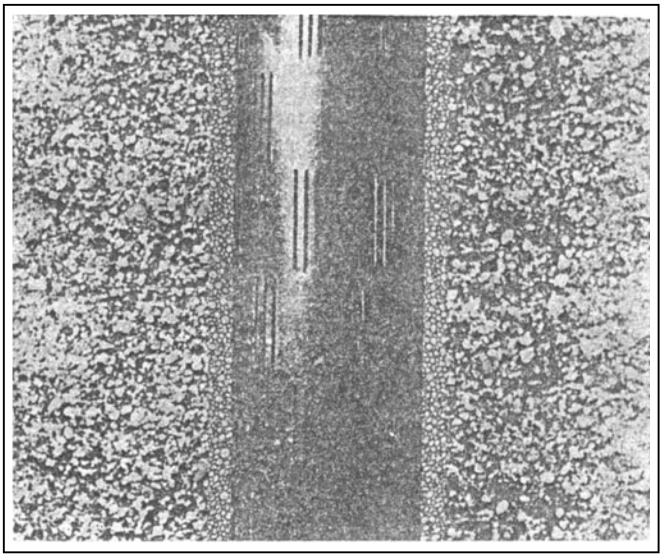

Fig. 6.1 A gravel packed tube well showing the effect of development. Development removes the smaller particles and leaves the coarser material with increased hydraulic conductivity around the slotted pipe

The basic principle in well development is to cause the rversal of flow, through the screen opening, that will re-arrange the formation particles. It is essential to break down the bridging of groups of particles. Figure 6.2 shows how small sand particles can bridge large sand and gravel particles and well screen openings when the flow of water is in one direction only.

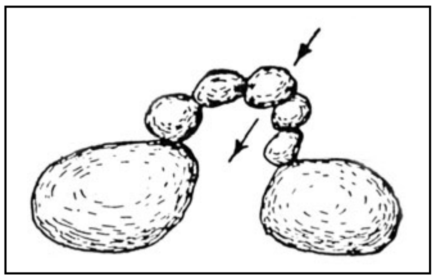

Fig. 6.2 Bridging action caused by arches of sand grains when the flow is in one direction only

Reversing the direction of flow by surging the well overcomes this tendency. The outflow portion of the surge cycle breaks down bridging and the inflow portion then moves the fine material towards the screen and into the well.

An important factor in any method is that the development work be started slowly and gently and increased in vigour as the well is developed. The development should be started, as far as possible, from the bottom of the screen because compaction would then take place as the work progresses upward, and the overlying material can move downward without much possibility of bridging. Should a bridge develop, the development action would usually break it up.

Development should continue until the discharge water is clear and all fine material from the well and adjacent aquifer have been removed. The time required for development depends on the nature of the water bearing layer, the thickness of screen slots relative to aquifer particle size, the amount of material raised from the well prior to placing the filter pack, and the type of equipment and degree of development desired. Large amounts of development energy are required to remove drilling fluid containing clay additives (Driscoll, 1986).

6.2 METHODS OF WELL DEVELOPMENT

The commonly used methods of developing tube wells are given below:

1. Over-pumping (with pump)
2. Surging (with surge block and bailing)
3. Surging and pumping (with air compressor)
4. Back-washing
   - with pump (rawhiding)
   - under pressure
   - with compressed air
5. High velocity jetting
6. Fracturing
   - Blast enhanced
   - Pneumatic
   - Hydro
   - Liquified CO_2
7. Chemical treatment

6.2.1 Over-Pumping

The over-pumping method of well development is commonly used to remove fine particles from formations close to well screens, especially in case of shallow tube wells. The method is preferred by users because of its simplicity, though it is not as effective as other methods.

Development Procedure

The procedure involved in well development is to operate the tube well at a discharge higher than its design capacity, except wells in hard rock which are developed at normal discharge. The over-pumping may be continuous or interrupted. Continuous over-pumping means pumping the well continuously at a rate not less than 50 per cent in excess of its normal discharge, except in hard rock. Shallow tube wells are often pumped with the same pump which is to be installed in the well after development. Since a higher input horse power is required, farmers often use tractors as prime movers during well development. In case of deep tube wells, vertical turbine pumps equipped with gear drive and directly connected to diesel engines through telescopic shafts are used.

In case of interrupted over-pumping, well development is done with a pump capable of pumping at rates up to twice the design capacity (except wells in hard rock). The development is carried out in at least 5 steps. These steps may include pumping rats of $\frac{1}{4}$, $\frac{1}{2}$, 1, $1\frac{1}{2}$ and 2 times the design capacity, without using check or foot valves. Pumping may be conducted in 5-minute cycles and should continue for a minimum of 2 hours or until such time as acceptable standards are achieved.

The main lacuna of development with over-pumping is that the flow velocity induced is only in the radial direction. Hence, fine particles are removed in the direction of the well. Continuous pull on the sand grains in one direction results in wedging of sand grains against each other and across the opening of the screen. Because of this limitation, well development by over-pumping has not proved very effective in the development of large-capacity tube wells, especially those drilled with direct rotary drills. In such wells, mud cakes are formed and may not break by over-pumping.

The only way in which wedging of sand grains may be prevented is by back-washing. The method consists of starting and stopping the pump intermittently to produce relatively rapid changes in the pressure head in the well.

Adaptability

This method is of special advantage for shallow tube wells with coir strainers, as such wells cannot withstand the pressure of the air compressor. For higher capacity wells, its use is limited to wells drilled with reasonably clear circulating fluid which does not form a filter cake or permeated mud.

6.2.2 Surging with Surge Block and Bailing

Surging consists of working a block or plunger up and down in the tube well so that water is alternatively forced into the surrounding formation and then allowed to flow back into the well. The surging action loosens fine sand or gravel particles near the well screen and carries the finer particles into the well from where they can be removed.

Equipment for Surging

The tool normally used in surging is a surge plunger or surge block (Fig. 6.3). A heavy bailer may be used to produce the surging action, but is not as effective as a close-fitting surge block.

Surge blocks may be of two types: (i) a solid plunger and (ii) a plunger with valve opening. A simple solid plunger may be made by wrapping sack cloth, old rope or some such material around the drill stem or a bailer. Such simple plungers may be employed where well development is easy.

The solid plunger (Fig. 6.3) may be built by sandwiching two leather or rubber belt discs between wooden discs assembled over an extra-heavy pipe nipple with steel plates serving as washers under the end couplings. It is desirable to provide a clearance of 5-12 mm between the inner wall of the casing pipe and the plunger flanges.

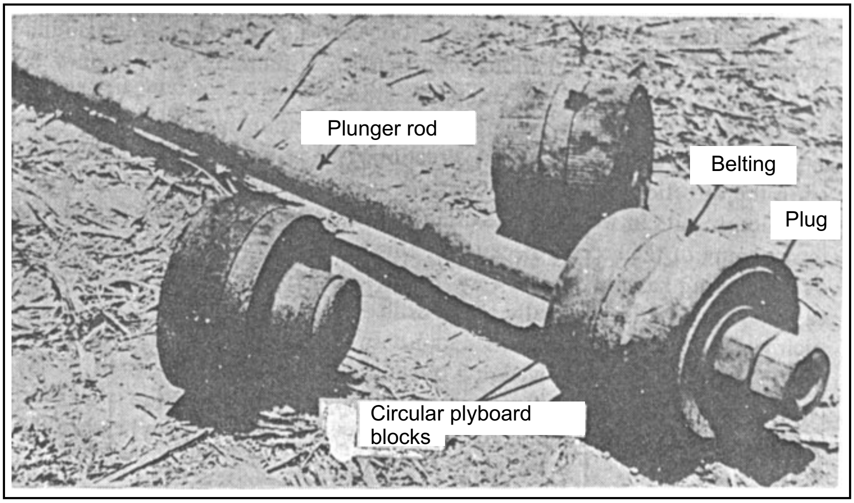

Fig. 6.3 Solid type plunger used in developing tube wells

The valve-type plunger (Fig. 6.4) differs from a solid plunger only in terms of two port holes of about 20 mm diameter drilled through the rubber and wooden discs. These holes are covered with rubber washers on the top. The valve-type plunger pulls water into the screen in the same manner as the solid plunger in the upstroke. But its surging action on the downstroke is milder because some water passes up through the ports in the plunger. By this method, comparatively less water is pushed back through the screen openings and into the formation.

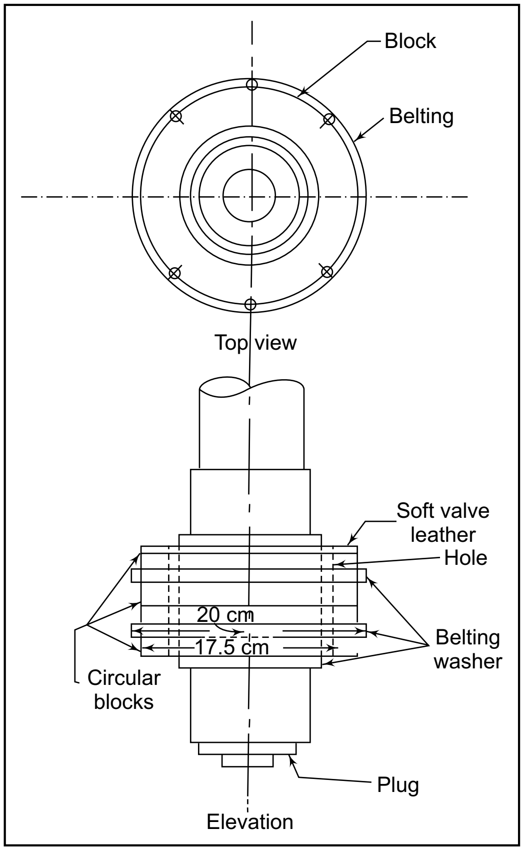

Fig. 6.4 Valve-type plunger used in tube well development

Development Procedure

The surge plunger is lowered into the tube well so that it is 3-5 metres under water, but above the top of the well screen. In case of wells with long screens, the surge plunger may be operated inside the screen for effective development at various depths (with care and safety to avoid damage of the screen). The action of the plunger is transmitted to the well screen by the water column. Surging is started slowly. The speed is gradually increased, keeping it within the limit at which the plunger will rise and fall smoothly without jerking. When a rotary rig is used, the plunger is lifted to about one metre and dropped, using the hoist break and clutch or by manipulating a rope around the cat-head of the drill. After surging for 10 to 15 minutes, the plunger is taken out and a bailer lowered to the bottom of the well to estimate the quantity of sand accumulated in the well. The sand is then bailed out. The process is repeated, gradually increasing the period of surging until little or no sand is pulled in. The development period may vary from a few hours for small wells to a few days for large wells.

Adaptability

Well development by surging is easy to apply and requires simple equipment. The type of plunger to be used depends on the aquifer formation. The solid plunger does not work effectively in wells tapping low-yielding aquifers. This is because the formations are not able to absorb the quantity of water being pumped in by the plunger on its downward stroke. In such aquifers, a valve-type plunger should be used.

The surging method of well development has been observed to be ineffective in tube wells with thick gravel pack because the water that is pushed through the slots slashes up and down the pack instead of into the sand. This method should not be used for development of wells in case of aquifers having streaks of clay and fine sand formations. It is useful for the development of strainer wells or wells with a limited thickness of gravel pack.

6.2.3 Surging and Pumping with Compressed Air

Surging with compressed air is a combination of surging and pumping. In this case, a large volume of air is released suddenly into the well casing pipe, which produces a strong surge. Pumping is done with an ordinary air-lift pump. To achieve successful development of the well, the submergence ratio (length of airline in water divided by its total length) is important. The efficiency of development reduces rapidly if the desired submergence ratio is not maintained.

Equipment

The equipment required for surging and pumping operations consists of an air compressor and tank of the required size, drop pipe and an air line with a suitable arrangement for raising and lowering each independently, flexible high-pressure air hose for the supply of compressed air to the air pipe, pressure gauge, relief valve and a quick-opening valve in the outlet of the tank. The set of the equipment for well development by surging and pumping is shown in Fig. 6.5. A T-joint is fitted with the educator pipe (Drop pipe). The discharge pipe is fitted with the side outlet of the T-joint. The top of the T-joint is screwed with a bushing which has its inside opening large enough to house the coupling of the air-line. A sack is wrapped around the line, where it enters the drop pipe, in order to reduce spraying of water above the top of the well. The air tank of the air compressor is connected to the airline through a high-pressure flexible hose pipe and a quick-opening valve near the tank.

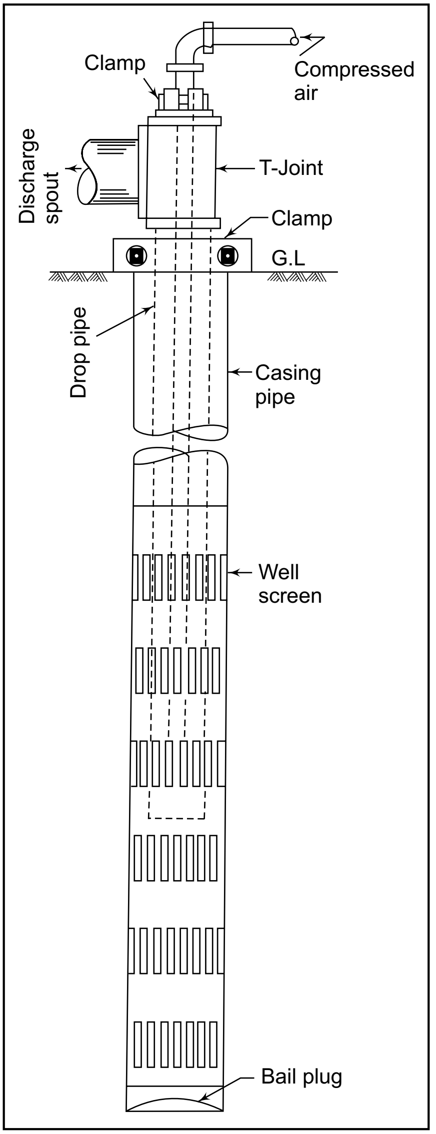

Fig. 6.5 Well development with compressed air (Surging and pumping)

Per cent Submergence

The principles of operation of an air lift pump is shown in Fig. 6.6, where,

A = depth of airline below the water level at which the water stand when pump is in operation, m

D = drawdown, m

L = net height of lift, m

H = height of the column of air-water mixture, measured from air inlet to point of discharge, i.e. $H = A + L$, m

$A + D$ = depth to which an airline is lowered below the normal level of the water before pumping, m

To start pumping, air pressure must be sufficient to overcome the normal static head, $A + D$. When flow has started, the pressure required falls to A.

$$\therefore \text{Starting pressure} = \frac{A+D}{10}, \text{ kg/cm}^2 \tag{6.1}$$

$$\text{Working pressure} = \frac{A}{10}, \text{ kg/cm}^2 \tag{6.2}$$

Assuming that the water rises in piston-like masses, the total length of their masses in column H must be theoretically equal to the outside solid column of water A (neglecting the weight of the compressed air contained in the column). But to overcome the frictional resistance and produce flow, the head A must be slightly higher. Under ordinary working conditions, the net height of lift L is generally within the range of 0.5 to 0.65A. Taking the lower value of submergence,

$$L = 0.65\,A \tag{6.3}$$

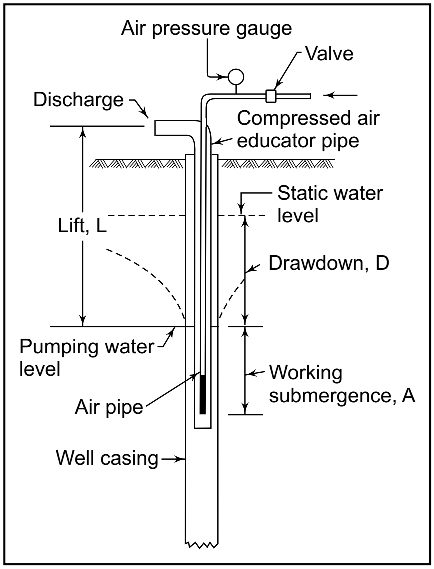

Fig. 6.6 Principles of operation of an air-lift pump

The percentage submergence while starting and during operation are of importance. They are calculated as follows:

Starting percentage submergence

$$= \frac{\text{Starting submergence, m}}{\text{Starting submergence, m + Starting lift, m}} \times 100$$

$$= \frac{A+D}{A+D+(L-D)} \times 100 = \frac{A+D}{A+L} \times 100 \tag{6.4}$$

Working percentage submergence

$$= \frac{\text{Working submergence, m}}{\text{Working submergence, m + Working lift, m}} \times 100$$

$$= \frac{A}{A+L} \times 100 \tag{6.5}$$

Substituting the value of L from Eq. (6.3) in Eq. (6.5),

Working percentage submergence

$$= \frac{A}{A+0.65\,A} \times 100 = \frac{1}{1.65} \times 100$$

$$= 60.6 \quad \text{say } 60$$

Hence, the optimum working submergence should be about 60 per cent for achieving the best results in well development.

The submergence requirement of the air line for achieving successful development of a well, as recommended by Bharatan (1963), is given in Table 6.1.

TABLE 6.1 Recommended Submergence of Airline for Development of Wells with Compressed Air

Lift m	Maximum submergence %	Optimum submergence %	Minimum submergence %
6	70	66	55
10	70	66	55
15	70	66	50
20	70	64	50
25	70	63	50
30	70	60	45
40	65	60	45
50	65	60	45
60	60	50	40
70	55	50	40

Source: Bharatan (1963)

Selection of Air Compressors

The two most important factors in the selection of an air compressor for well development are the requirement of pressure and capacity. The required air pressure is determined, based on the length of air pipe below the static water level. Before air can be discharged from the lower end of the air pipe, the compressed air must push all the water out of the pipe. To do this, the air pressure must be greater than the water pressure before starting to pump water. The required pressure (excluding pressure drop in air-line) is given by Eq. 6.1.

A useful rule of thumb to estimate the compressor capacity is to provide about 0.28 m^3/h of free air for each litre per minute of water at the anticipated pumping rate (Example 6.1).

Messrs Ingersoll Rand and Co. (Sanwal, 1945) have evolved the following empirical formula for determining the quantity of air required for lifting water with an air compressor:

$$V = \frac{0.0203\,h}{C \log \dfrac{H + 34}{34}} \tag{6.6}$$

where, V = quantity of free air required per litre of water lifted, m^3

h = total lift including friction losses, m

C = constant, depending upon the percentage working submergence, as given in Table 6.2.

H = working percentage submergence, %

TABLE 6.2 Value of Constant *C* in Eq. (6.6)

Working percentage submergence	75	70	65	60	55	50	45
Value of constant C in Eq. (6.6)	366	358	348	335	318	296	272

Example 6.1 A tube well drilled in an alluvial formation has anticipated discharge of 40 1/s. It is proposed to develop the well with an air compressor. The depth of water from the static water level to the lower end of the airline is 80 m. Determine the specifications of the air compressor required.

Solution

(i) Pressure required = 80/10 = 8 kg/cm^2, or about 10 kg/cm^2 (to take care of pressure drop in the air pipe)

(ii) Capacity of air compressor at 0.28 m^3 per hour for each litre discharge per minute = $0.28 \times 40 \times 60$ = 672 m^3/h

Therefore, a compressor of about 700 m^3/h in capacity and an operating pressure of 10 kg/cm^2 is to be chosen. Often the air compressor available with tube well organisations are of lower capacity. In that case, more than one compressor could be used for developing a tube well.

Sizes of Pumping and Airline Pipes

The following are the recommended sizes of pumping pipes and the sizes of the air lines for different pumping rates.

Pumping rate l/s	Diameter of pumping pipe, mm	Diameter of air line, mm
7.5 – 12.0	100	30
12.0 – 17.5	125	40
17.5 – 30	150	50
30 – 55	200	60

Development Procedure

To start the development operation, the drop pipe and the air line are lowered to obtain the desired submergence. The bottom of the drop pipe is kept about 60 cm above the bottom of the screen. The air line is kept about 30 cm higher than the bottom end of the drop pipe. Air is then turned on and the well pumped (Fig. 6.7) by the conventional air lift principle until the discharge water is free from sand. Air entry into the well is then cut off by closing the valve between the tank and the compressor. In the mean-time, the airline is lowered so that it is about 30 cm below the bottom of the drop pipe. The airline is thus at the same position as in the back-washing method. The air valve is quickly opened to allow the compressed air from the tank into the well. This tends to surge water outwards through the well screen openings. The air pipe is raised again and the cycle repeated until the water discharge from the well is relatively free of sand. The above operation of back-washing and pumping completes one operation of surging. The entire assembly is then raised to a height of about one metre and the operations repeated until the well section along the entire length of the screen has been developed. Finally, the air pipe is lowered again to the bottom of the well and the equipment operated as a pump to flush out any sand that might have accumulated inside the screen.

Adaptability

The surging and pumping method of well development with compressed air is widely used for the development of tube wells drilled by any of the common methods, in alluvial formations. Shallow tube wells with coir strainers, however, cannot withstand the air pressure exerted in surging. This method has its limitations where the yield is very low and the drawdown rapid, or where submergence is low.

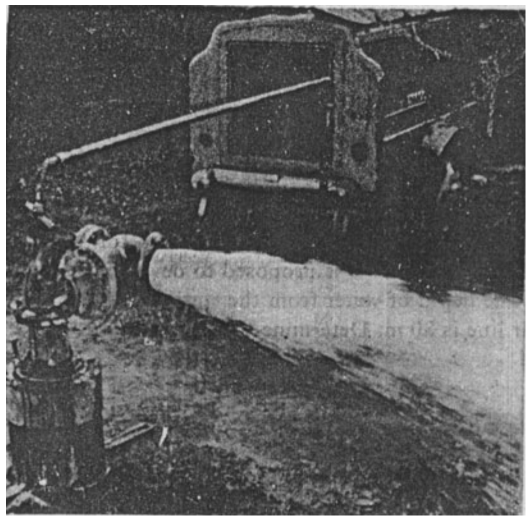

Fig. 6.7 Tube well development with compressed air

6.2.4 Back-washing

In this method, water under pressure is forced into the well screen, which eventually passes out in the surrounding formation, cleaning the strainer and carrying with it fine sand particles which often clog it. It agitates the formation in the vicinity of the well, which causes the breakdown of bridging sand particles, and washes out the finer particles. It is an effective method of well development. The various methods employed for backwashing are: (i) back-washing by pumping (rawhiding), (ii) back-washing under pressure, and (iii) back-washing with compressed air.

(i) *Back-washing by Pumping (Rawhiding)*

The process of well development by back-washing by pumping, also called rawhiding, consists of starting and stopping the pump intermittently to produce relatively rapid changes in the water level in the well. While this may be done with any kind of pump, it is most effective with a turbine pump installed without a foot valve (Fig. 6.8). The following are the three main types of reactions obtained by operating the pump in different ways:

(a) The pump is operated at its full capacity until it has produced the maximum possible drawdown of the water level. It is then stopped. The well is permitted to regain its full static water level. This process is repeated until the well shows no further improvement in terms of specific capacity and sand pumping.
(b) The well is pumped to obtain the maximum possible drawdown. It is then stopped and started, alternately, at short intervals. This has the effect of holding down the water level in the well and frequently agitating the formation by the back-wash of the water in the pump column.
(c) The well is pumped and as soon as the water starts coming out of the delivery pipe, it is stopped without waiting for the maximum drawdown to be attained. The falling water column causes some reversal of flow, resulting in agitating the formation around the well screen. This method is most effective when the static water level is very deep so that the high water columns contain sufficient quantity of water and the water level falls quickly.

All the three techniques described may often have to be tried on a particular well. Depending upon the result, any one or a combination is adopted for the best results. Sometimes, if a considerable amount of sand is pumped with the water, the pump will be subjected to excessive wear, which reduces its efficiency. Under severe conditions, the pump may get sand-locked. Should this occur, the pump must be pulled out, disassembled and cleaned carefully before being put back into service.

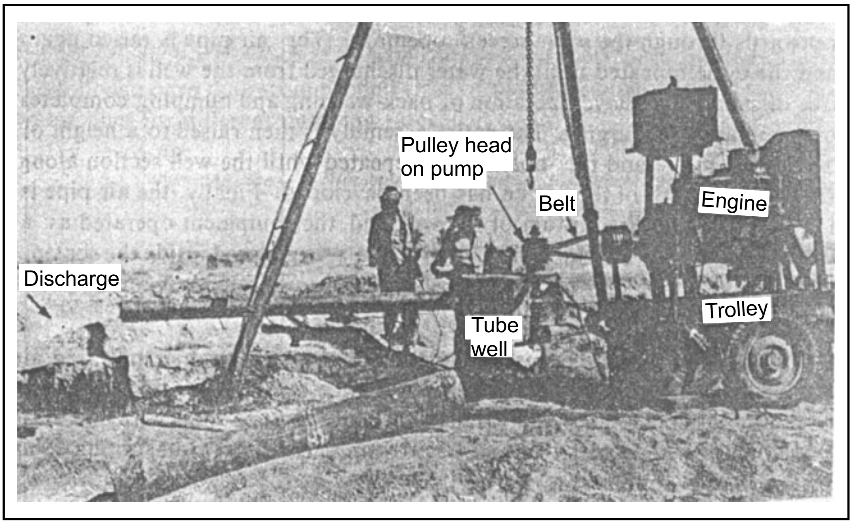

Fig. 6.8 Developing a tube well using a vertical turbine pump

(ii) *Back-washing under Pressure*

In this method, water is fed into the well, under pressure, by connecting a pump or hose line from a source of supply directly to the casing pipe (Fig. 6.9). As large a quantity of water as can be built-up safely is fed under high pressure. After a few minutes of feeding water, the connection is removed and the well pumped out vigorously. Sometimes water is fed into the well, under pressure, through a hose pipe, from a source of supply, by providing the top connection with a side valve outlet. A wash line (pipe length) is suspended at the bottom of the well for feeding water to the aquifer through the well screen. In this case, fine sand, silt and clay that have entered into the well are removed hydraulically by opening the side outlet valve. The method is forceful and effective. However, care should be taken to avoid damage to the well screen by back-washing under pressure.

(iii) *Back-washing with Compressed Air*

The set-up of equipment for the development of a well using the method of back-washing with compressed air is shown in Fig. 6.10. The principle of back washing is to force water back into the well, through the screen, and into the water-bearing formations by means of compressed air. Compressed air is introduced into the well through the top of the casing pipe, after it has been closed with an air-tight cover provided with flanges and a gasket. Two holes are bored in the cover. Over the larger hole, a T-joint of the size corresponding to the size of the drop pipe is welded. The drop pipe extends downward from the T-joint to the top of the well screen. Thus, by terminating the drop pipe at the top of the screen, a point of relief is provided to the air introduced into the casing during back-washing. This will prevent air-logging which could force large volumes of air into the aquifer and hold back normal movement of water.

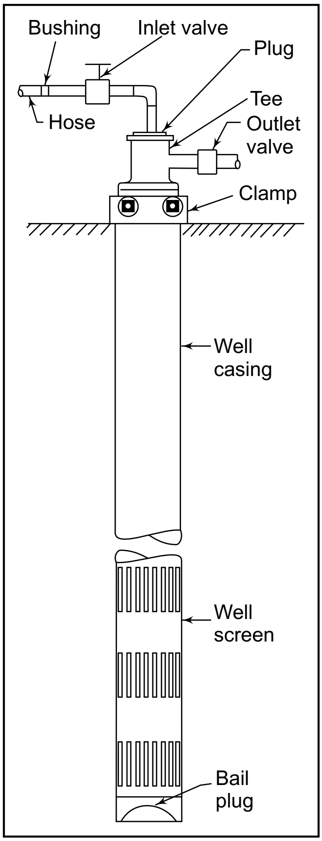

Fig. 6.9 Tube well development by back-washing under pressure

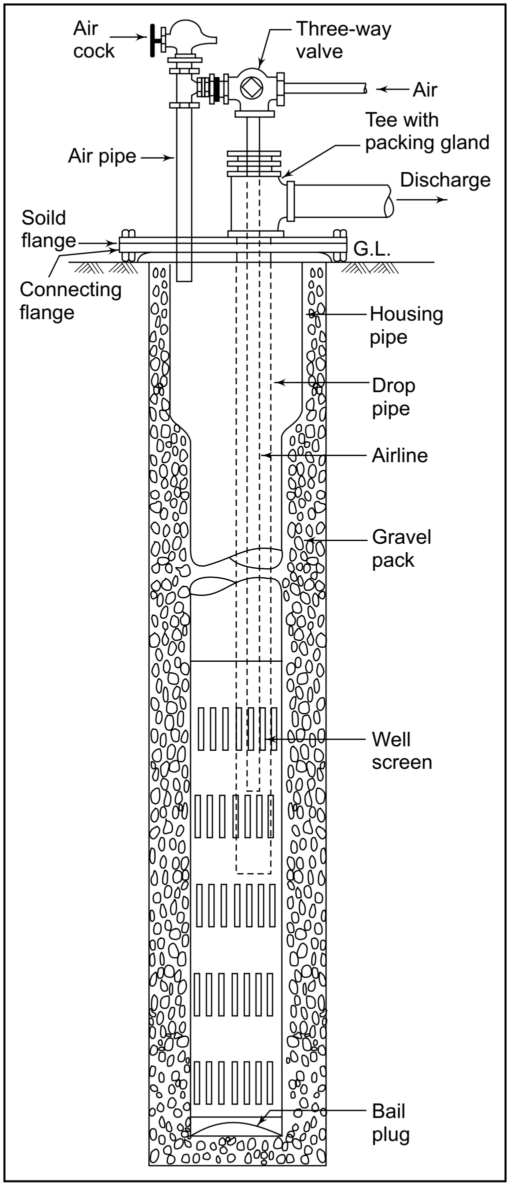

Fig. 6.10 Tube well development by back-washing with compressed air

The upper end of the T-joint is provided with a packing gland, through which the airline is passed down to a point within half a metre above the bottom of the drop pipe. A separate short air pipe is welded to the small hole provided in the flange (Fig. 6.10). A 3-way valve is provided for controlling the compressed air. The inlet of this valve is connected to the air delivery line, from the source of compressed air. The side outlet is connected to the upper end of the air line. The end outlet is connected to a T-joint fitted with a short air line. The T-joint is provided with an air cock at the other opening.

Development Procedure

Air is released through the long air pipe, forcing air and water out of the well through the discharge pipe. After the water clears, the air supply is shut off and the water allowed to return to its static level. A 3-way valve is then turned to admit air into the top of the well through the short air pipe. This forces the water back through the screen into the formation to break the bridges of fine sand. The water level will not go below the bottom of the drop pipe as air will start escaping through the drop pipe as soon as the water level goes below this level. Air is forced into the well until it begins to escape from the discharge pipe, after which the three-way valve is turned off and the air supply is again directed down the long air pipe to pump the well. Back-washing is repeated until the well is fully developed.

Adaptability

Development by back-washing with compressed air is commonly used for wells drilled by direct rotary drilling rigs. Back-washing helps break the mud cake and remove the mud penetrated into the formation. However, for wells with excessive thickness of gravel pack, this method is ineffective. If the stratum above the aquifer comprises silt, sandy clay or similar materials, back-washing should not be tried, as it might wash in the undesirable material and cause caving-in and clogging of the gravel pack.

6.2.5 High-Velocity Jetting

Jetting with water at high velocity is an effective method of development of tube wells. The method has the advantage of effectively applying concentrated energy over a small area. A relatively simple jetting tool (Fig. 6.11), together with a high-pressure pump and the necessary hose and piping are the principal items of equipment required. The jetting tool contains 2, 3 or 4 horizontal jets.

The high-velocity jet, working through the screen openings, agitates re-arranges the sand and gravel particles of the formation surrounding the screen. The mud cake deposited on the walls of the bore hole in the conventional rotary drilling is broken effectively and dispersed so that the drilling mud deposited around the well strainer can be pumped out easily. The jetting action also corrects the damage to the formation resulting from any of the other methods of drilling.

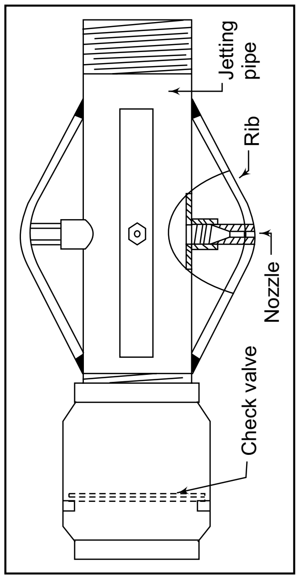

Fig. 6.11 Details of jet assembly provided with check valve

Development Procedure

The procedure for well development (Fig. 6.12) consists of operating a horizontal water jet, inside the well in such a way that the high velocity stream of water shoots out through the screen openings. By slowly rotating the jetting tool and gradually raising or lowering it, the entire surface of the well screen gets agitated by the jet. Fine sand, silt and clay are washed out of the water-bearing formation. The turbulence created by the jet brings these fine materials back into the well through the screen opening above and below the point of operation. The jetting tool is rotated by adjusting a clamp at the top, and is gradually raised or lowered until the entire surface of the screen is covered. When the jetting operation is in progress, it is desirable to pump the well lightly to create a drawdown to induce the movement of water into the well and pump out the loosened materials. A conventional centrifugal pump or an air-lift pump can be used to operate the system.

Jet Assembly

The jet assembly comprises a jetting tool and a string of pipes. The bottom of the jetting tool is either closed or provided with a check valve (Fig. 6.11). The check valve facilitates the removal of the products of development from the well. While this does not permit simultaneous jetting and pumping, it makes easier and faster a change over from jetting to pumping. The upper end of the jetting tool has threads so that it can be screwed to the lower end of the string of pipes. An alternate method uses an offset jetting line (Fig. 6.13). The purpose of this tool is to provide extra space for a pump. The diameter of the jetting tool is about 2–4 cm less than the inner diameter of the well screen. Generally, the diameter of the jetting pipe varies from 3.75–7.5 cm, depending upon the length of the pipe and discharge it has to carry. The nozzles are designed by adopting the procedure described below:

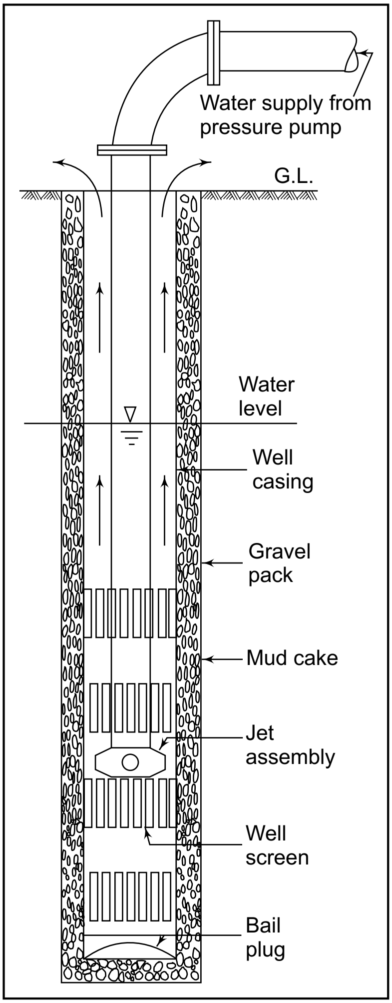

Fig. 6.12 Well development by high velocity jetting

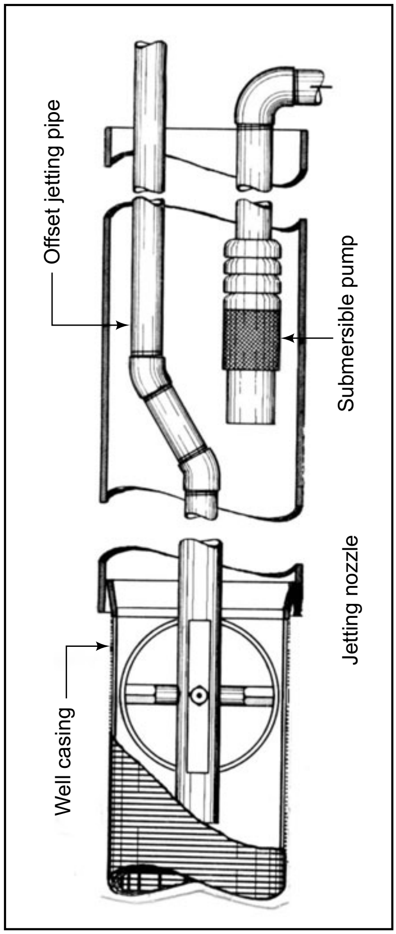

Fig. 6.13 Use of offset jetting pipe in jet method of tube well development

The diameter of the nozzle/orifice is selected on the basis of the normal jet discharge (per nozzle) and velocity, as a function of operating pressure, as indicated in Table 6.3.

TABLE 6.3 Relationship between Nozzle Size and Jet Discharge and Velocity in Well Development by High-Velocity Jetting

Nozzle orifice	Pressure, kg/cm^2					
	7		14		17.5	
size mm	Velocity m/s	Discharge l/s	Velocity m/s	Discharge l/s	Velocity m/s	Discharge l/s
6.25	34.0	80	45	120	55	190
10.0	34.0	175	45	250	55	275
12.5	34.0	300	45	450	55	500

However, for a given discharge and assumed velocity, the diameter of the jet can be computed on the basis of the following relationships:

$$Q = 0.9\, a\, \sqrt{2\, gh} \tag{6.7}$$

where, Q = discharge capacity of the jetting pump, m^3/s

a = area of jet, m^2

h = hydraulic head including friction losses, m

The friction head H_f may be computed by the Darcy-Weisbach formula,

$$H_f = \frac{4\, fl\, v^2}{2\, gd} \tag{6.8}$$

where, f = Darcy's coefficient of friction in pipe

v = velocity of jet, m/s

d = diameter of pipe, m

g = acceleration due to gravity, 9.81 m/s^2

Adaptability of Jetting Method

The high-velocity jetting method is suitable for development of wells drilled in layered, fine-grained or clayey aquifers. However, for development of deep wells, a high delivery head pump is required. Secondly, excessive pressure should not be used in jetting. A pressure of 15 kg/cm^2 is considered the upper limit.

Example 6.2 A jetting tool with four nozzles at the end of a 4-cm diameter pipe is to be used to develop a tube well under a head of 120 m. The discharge capacity of the pump is 31/s. Determine the size of each nozzle.

Solution

The area of the jet is computed using Eq. (6.7):

$$a = \frac{Q}{0.9\sqrt{2gh}}$$

$$= \frac{0.003}{0.9 \times \sqrt{2 \times 9.81 \times 120}} \text{ m}^2$$

$$= 0.000068 \text{ m}^2$$

$$\text{Area of each nozzle} = 0.000068 \div 4$$

$$= 0.000017 \text{ m}^2$$

$$\therefore \quad \text{Diameter of each nozzle} = \sqrt{\frac{0.000017 \times 4 \times 7}{22}}$$

$$= 0.00465 \text{ m}$$

$$= 4.65 \text{ mm}$$

Example 6.3 A jetting tool, with four 7.5-mm nozzles at the end of a 5-cm diameter pipe, is required to work at a depth of 120 m. If the jet velocity to be obtained is 40 m/s, determine the capacity of the pump required. Assume friction factor for the pipe to be 0.01.

Solution

$$\text{Discharge through four nozzles} = 4 \times V \times a = 4 \times 40 \times \frac{\pi}{4}(0.0075)^2$$

$$= 0.007 \text{ m}^3\text{/s}$$

$$\text{Velocity in 5-cm diameter pipe} = \frac{\text{Discharge}}{\text{Area}} = \frac{0.007}{\frac{\pi(0.05)^2}{4}} = 3.57 \text{ m/s}$$

$$\text{Friction loss} = \frac{4flv^2}{2gd}$$

$$= 4 \times 0.01 \times \frac{120}{0.05} \times \frac{(3.57)^2}{2 \times 9.81}$$

$$= 62.4 \text{ m}$$

Total head to be delivered by the pump

$$= 120 + 62.4 = 182.4 \text{ m}$$

Hence, a pump of 0.007 m^3/s (7 l/s) capacity with a total head of 182.4 m is required.

6.2.6 Fracturing

Fracturing was originally developed for the oil and gas industry to increase oil and gas well production. It is relatively new technique adopted by the water well industry. Fracturing is a water well development process designed to increase the efficiency of water wells in hard rock areas. It is primarily used to enlarge existing fissures and introduce new fractures in the bedrock thereby enlarging the network of water bearing fractures supply water to the well. The new fractures occur primarily in the horizontal direction and they facilitate the movement of water towards well. Fracturing is a cost effective means of increasing the yield of existing wells with insufficient discharge, or existing older wells with decreased discharge due to incrustation or mineralizations of existing bedrock fractures. Common fracturing techniques are:

1. Blast-enhanced fracturing
2. Pneumatic fracturing
3. Hydro-fracturing
4. Liquified CO_2 injection

Blast-Enhanced Fracturing

Blast-enhanced fracturing is used at sites with fractured bedrock formations. Bore-hole are drilled, filled with explosives, and detonated to create fractures. In granite and genesis formations, water flows through cracks, joints and fissures. They can be opened by shooting a charge of dynamite opposite the flow zone.

Pneumatic Fracturing

In pneumatic fracturing process, wells of 0.6 m diameter are drilled. Small portion of the zone receive short bursts of compressed air. This fractures a small radius surrounding each well. The process is repeated throughout the zone.

Hydro-Fracturing

Hydro-fracturing involves injecting high pressure water via the well into the bedrock formation immediately surrounding it. The process creates fissures, which expand away from the wells. The procedure involves the lowering of one or two inflatable hard rubber balloons or packers as they are called, on a pipe down into the well bore. These packers are inflated to seal off a section of the well. The packers are set at minimum of 7 m below the end of the casing and 20 m below ground surface to prevent a breakout of water under pressure and surface water entering the well. High pressure water is pumped through the packer. The pressure within the sealed off section of the well will rise as the formation resists flow into it. At some higher pressure, the pressure will suddenly drop off indicating that the formation is accepting water and resistance to flow has decreased. Water is pumped into the formation from 5 to 45 minutes at a rate of 100 to 200 litres per minutes. Up to 6000 litres of water can be pumped into the formation. Indications of a successful hydro-fracturing procedure are a sudden drop in the pressure combined with increased flow into the formation, and a strong backflow of cloudy water when pressure is released. If the pressure increases to the maximum working pressure (210 kg/cm^2) of the equipment with no sudden drop in pressure, then the hydro-fracturing procedure may have been unsuccessful.

When a single packer is used, the packer is set near the top of the well. Applying pressure in this manner to the well bore means that the weakest fracture or the fractures of least resistance would be affected. Usually the packer is then moved down the hole to hydro-fracture another section of the well. This may be fine for domestic well purposes since the cost for single packer hydro-fracturing is less than when a double packer system is used. When using a double packer system, the packers are situated on a pipe called a drill string, typically 14 to 20 m apart. A selected zone in the well can be pressured by inflating both packers and then when done, the packers are deflated and moved elsewhere in the well bore to pressure another section of the well. This system is more efficient since discrete sections of the well bore are hydro-fractured. A number of zones can be hydro-fractured in this manner. The packers are usually first set near the bottom of the well and moved up the bore to isolate another interval of the well for hydro-fracturing. Information on specific sections of the well to be hydro-fractured can be obtained from the well drillers log. The well log will indicate at what depths the water was found to be entering the well. The use of a downhole camera is also helpful in determining where suitable fractures exists in the bore and if there are flow of water.

Liquified CO_2 Injection

In this process, the liquified CO_2 is injected into water producing formation which has been isolated by inflatable packers. It freezes the surrounding water, opening nearby fractures. As the liquid CO_2 becomes a gas, it expands into the formations, opening them further. This process work best when coupled with surging or air development.

6.2.7 Chemical Treatment

Chemical agents are introduced in the development zone as solver. Their action is intended to dissolve or loosen any clogging or blocking materials to make them easier to remove. The action of chemicals may also enlarge aquifer pores and improve permeability. Chemical based well development techniques can be gentle or violent in their action.

Chemical methods are often used in conjunction with other well development techniques. Specifically, when additional action is needed to break up mud cakes or flush out gelled muds. The chemical solution is allowed to stand in contact with the aquifer for the recommended time period. After this, the solution is pumped or bailed from the hole. While well drilling fluids will break down naturally, the breakdown process may be enhanced by the use of chemical agents. Once degraded, the drilling fluids are much more easily pumped from the aquifer. Other chemicals may be used to break down clay smears or gelled bentonite. Chlorine breaks down polymers.

A tremie pipe may be used in conjunction with packing devices to isolate the areas of the bore-hole to be subjected to chemical treatment. Chemical treatment can be used to breakdown drilling fluids, clays and polymers. Acids are often used for improving the yield in limestone, dolomite and other calcium carbonate formations. However, acid treatment cannot improved the yield in crystalline rock (granite, diorite, monzonite, etc.) formations.

There are several requirements that any chemical should meet if it is to be used for treating water wells. First, of course, it should be effective in dissolving, disintegrating and dispersing commercial drilling muds, clays and shales so that they can be easily bailed or pumped out. It should be capable of dissolving limestone and water deposited scales, corrosion products and organic growths. It should be relatively non-toxic and should not contaminate the water. It should be safe to use on the mechanical equipment in the well. It should also be safe and easy to handle.

6.3 USE OF DISPERSING AGENTS IN WELL DEVELOPMENT

Adding a small quantity of a suitable polyphosphate to the drilling mud or the water used in back-washing and jetting and to the water standing in the well helps considerably in the removal of mud while developing a well. The phosphates disperse the clay particles in the drilling mud and break its gel properties. The dispersing action counteracts the tendency of the mud to stick to the sand grains. Breaking the gel makes the mud more easily movable by surging and back-washing. The polyphosphates that work effectively in helping mud removal are tetra-sodium pyrophosphate, sodium tripolyphosphate, sodium hexametaphosphate and sodium septa-phosphate. About 2 kg of the chemical is added to 400 l of water. A large amount of phosphate does not give any markedly different results when used for mud dispersion.

6.4 DEVELOPMENT OF A CAVITY TUBE WELL

Development of a cavity well is the drawing out of sand from below the clay roof. As the sand is drawn out, a cavity is formed in the water-bearing stratum at the bottom of the clay roof. Generally, the depth of the cavity is very small (only a few centimetres), but the circular area is large.The volume of the formation developed is much larger than the area of the cavity. It is on the development of the formation around the cavity that the yield of the cavity well depends.

Air compressors or turbine pumps may not develop a cavity well satisfactorily, unless a small cavity has previously been created by means of a sludger. A centrifugal pump is usually better suited for developing a cavity well than an air compressor. The cavity should be developed slowly and with great care. Otherwise, sand is likely to rush into the casing and choke it. This may cause such a disturbance in the formation that the satisfactory development of a cavity may become impossible even after removing the initial mass of sand.

To begin with, the discharge of the pump is kept low. When the discharging water has become clear, the rate of pumping may be increased slightly, which may result in more sand being drawn out. This process is repeated until the normal drawdown is reached and the discharge is clear. The pumping operation may then be stopped for an hour or so and then resumed. The discharge after restarting may again contain sand. The operation may be continued till the water is clear again. The procedure may be repeated till the well is fully developed, as evidenced by the discharge being clear even on resumption of pumping after an interval.

6.5 CHOICE OF WELL DEVELOPMENT METHOD

Each method of well development has its advantages and disadvantages. One may prove better than the other under a specific hydrogeological condition and depth of boring. The summary of recommendations for development of various types of wells is given in Table 6.4.

TABLE 6.4 Summary of Recommendations for Development of Various Types of Wells

Method of development	Tube wells up to 100 m depth in alluvial formations		Tube wells from 151 to 200 m depth in alluvial formations		Tube wells from 201 to 500 m depth in alluvial formations		Wells in boulders and pebbles	Bore wells in hard rock	Remarks
	Artificial gravel pack	Natural pack	Artificial gravel pack	Natural pack	Artificial gravel pack	Natural pack			
1	2	3	4	5	6	7	8	9	10
Over-pumping	Effective	Effective	Satis-factory	Satis-factory	—	—	Most effective	Most effective	Specially recommended for shallow tube wells drilled with percussion rigs
Surging with surge block and bailing	Satis-factory	Satis-factory	Satis-factory	Satis-factory	Satis-factory	Satis-factory	—	—	Not recommended for wells with thick gravel pack, and where streaks of clay and fine sand formations are encountered
Surging and pumping with com-pressed air	Effective	Effective	Effective	Effective	Not very effective	Not very effective	Satis-factory	Satis-factory	Not recommended in case of very low yield, rapid drawdown and low submergence
Back-washing	Effective	Effective	Satis-factory	Satis-factory	Not very effective	Not very effective	Satis-factory	Satis-factory	Not recommended if the stratum above the aquifer comprises sandy clay or similar material
High-velocity jetting	Satis-factory	Satis-factory	Very effective	Very effective	Very effective	Very effective	Not effective	Not effective	Simultaneous pumping of silt and clay with air compressor is recom-mended
Fracturing	—	—	—	—	—	—	—	Effective	—
Chemical treatment	—	—	—	—	—	—	—	—	Effective in conjunction with other well develop-ment techniques

6.6 TESTING OF TUBE WELLS

Following the development of a new well, it should be tested to determine its yield and drawdown. This information provides the basis for determining the water supply available from the well, for selecting the type of pump, and for estimating the cost of pumping. The information to be obtained from a well test includes the depth to static water level and the yield and depth of water when the well is pumped at different rates. From these data, the drawdown, yield and specific capacity (i.e. the yield per metre of drawdown) can be computed. In deep wells tapping substantial thicknesses of water-bearing strata, the yield is almost directly proportional to the drawdown. This, however, is not true, in general, for shallow wells (Fig. 6.14).

The well-characteristics curve is obtained by plotting the data on discharge versus drawdown. Typical characteristics curves of deep and shallow wells are shown in Fig. 6.14.

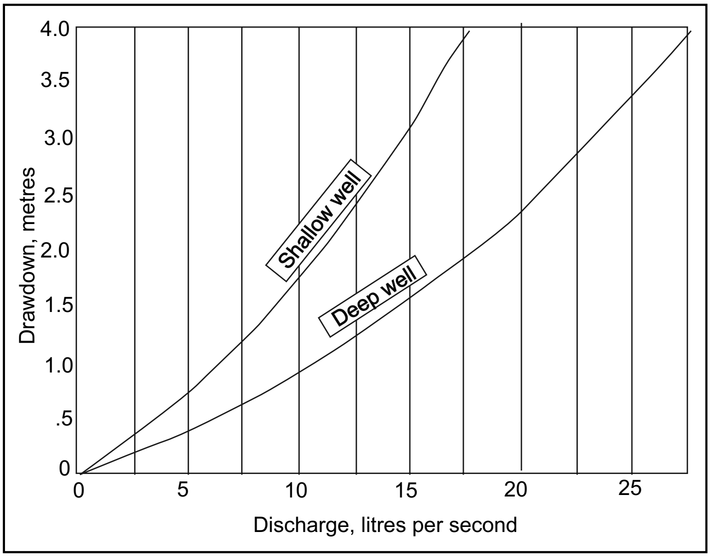

Fig. 6.14 Typical characteristics of shallow and deep tube wells

6.6.1 Measurement of Discharge and Drawdown

Well discharge can be measured by any of the conventional water-measuring devices like weirs, Parshall flumes, V-notches or orifices. The depth of water in most wells may be measured with reasonable accuracy by using a steel tape with a weight to make it hang straight. The tape is chalked at the lower end and lowered into the well until about 30 to 50 cm is submerged. The wetted length of the tape, which shows up clearly on the chalked portion, is subtracted from the total length lowered below the reference point; this gives the depth to water. The difference between the depth of water at any stage of pumping and the depth of static water level will give the drawdown.

Depth to water table measurements can be precisely made by an electrical depth gauge (Fig. 6.15). An electrode is suspended in the observation well by a metallic cloth tape. The conductor terminal clip is fixed with the observation well. The electrical circuit is completed when the electrode touches the water surface, which is indicated by the galvanometer. The corresponding depth is read on the tape.

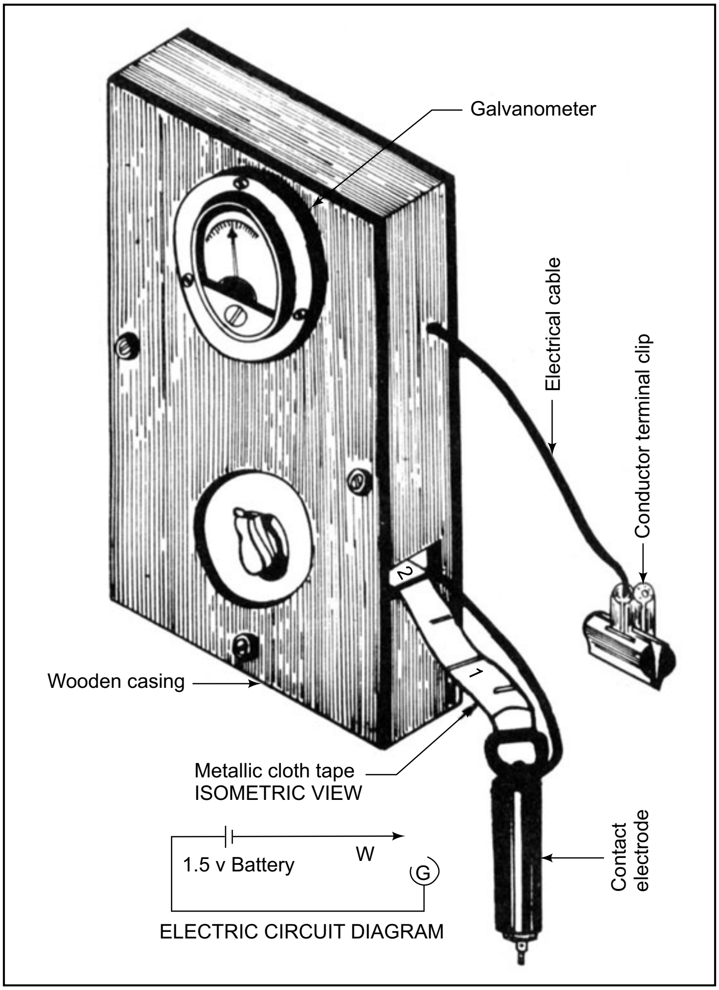

Fig. 6.15 Isometric view and electrical circuit diagram of an electrical depth gauge

In the case of horizontal centrifugal pumps directly connected with the well casing, drawdown can be determined by measuring the suction head with a vacuum gauge screwed on the suction side of the pump. The reading on the gauge will indicate the suction head from the centre of gauge. The suction head will include the head due to friction in the suction pipe. The component of the friction head may be estimated using Eq. (6.8). Making adjustments for the friction head and the distance between the static water level and the gauge, the drawdown can be estimated.

In the case of bore-hole pumps, where the casing is not directly connected to the suction side of the pump, the drawdown may be measured by means of an air line lowered into the annular space between the pump column and the well casing and fitted at the upper end with a pressure gauge (Fig. 6.16). The air line should extend about 3 m below the limit of drawdown. Air is pumped into the line until the maximum possible pressure is reached. Normally the air line is full of water up to the level of water in the well (static or pumping water level). When air is forced into the line, it creates pressure which forces water out of the lower end until it is completely expelled and the line is full of air. If more air is pumped in, air, instead of water, is expelled and it is not possible to increase the pressure further. The head of water, *C* or *E* (Fig. 6.16), above the end of the line maintains this pressure, and the gauge shows the pressure or head above the end of the line. If the gauge is graduated in metres of water, it registers directly the amount of submergence of the end of the line. This reading, subtracted from the length *A* of the line, gives the water level *B* or *D* (static or pumping water level). If the gauge is graduated in kg/cm^2, the reading must be multiplied by 10 to get the submergence in metres.

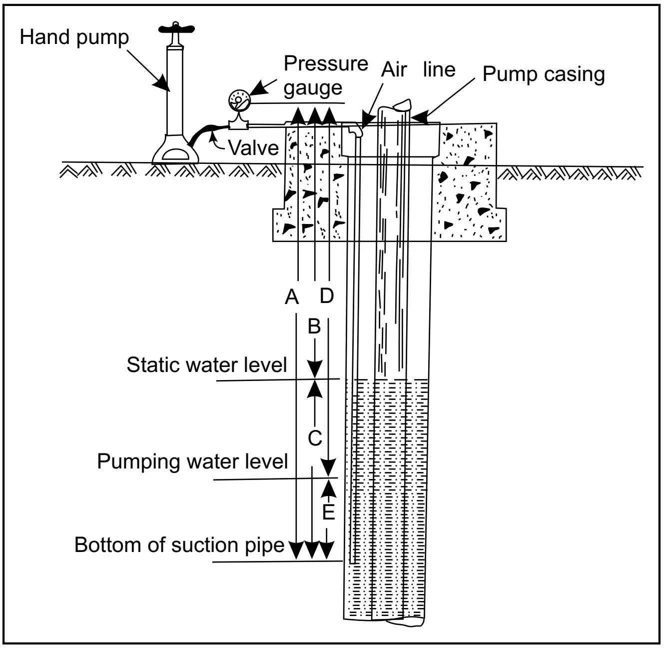

Fig. 6.16 Airline installed in a tube well for measuring water level

6.6.2 Test Results

The testing agency should furnish the results of tube well testing to the owner on completion of testing the tube well. Chemical and bacteriological analyses of the water should also be carried out. The test results should include rated discharge, depression at rated discharge, total hours run, sand in ppm at end of test, static water level and pumping water level under normal testing. The results of testing the tube well at a discharge higher than the normal should also be indicated. These results may include discharge, drawdown, total hours run, sand in ppm at the end of test, static water level and pumping water level.

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PROBLEMS

6.1 A tube well has been drilled in an alluvial formation. The expected discharge is 20 l/s. It is proposed to develop the well with an air compressor. The depth of water from the static water level to the lower end of the air line is 40 m. Determine the pressure requirement and capacity of the air compressor.

Ans. Pressure requirement ≈ 5 kg/cm^2
Capacity = 336 m^3/h

6.2 A jetting tool with four 7 mm diameter nozzles at the end of a 4 cm diameter pipe is required to work at a depth of 100 m. Determine the capacity and the total head of the pump required for operating the jet assembly. The jet velocity and the friction factor for the pipe may be assumed to be 35 m/s and 0.01, respectively.

Ans. Capacity of pump = 0.0054 m^3/s
Total head = 138.5 m

6.3 A jetting tool with four nozzles at the end of a 5 cm diameter pipe is to be used for the development of a tube well under a head of 150 m. The discharge capacity of the pump is 0.004 m^3/s. Determine the diameter of each nozzle.

Ans. Diameter = 5 mm

SHORT QUESTIONS

I. State True (T) or False (F).

1. Development of tube well increases the effective radius of the well.
2. The size of the particles in contact with the well screen decreases towards the aquifer after development.
3. The well development should be started from the top of the well screen.
4. Bridging action is caused by small sand particles.
5. Development of a tube well cannot correct its clogging.
6. Development is not necessary in all types of tube wells.
7. Cavity tube well do not require development.
8. The basic principle in well development is to cause the reversal of flow, through the screen opening.
9. The time required for development depends on the nature of water bearing layer.
10. Development action do not help in breaking bridge.
11. Over-pumping is an effective method of well development.
12. Surging action forces the water into the surrounding formation.
13. The solid plunger works effectively in wells tapping low yielding aquifer.

14. The surging method is useful for the development of tube wells with thick gravel pack.
15. For achieving the best results in well development, the submergence ratio should be about 60 per cent.
16. The required air pressure for well development increases with increase in the length of air pipe below the static water level.
17. Rawhiding is a process of well development.
18. Surging action cannot be applied for well development by using compressed air.
19. Well development by over-pumping may cause bridging of particles.
20. Over-pumping the well for development is better than back-washing by pumping.
21. Development of well by back-washing with compressed air is commonly used by wells drilled by direct rotary drilling rigs.
22. Back-washing helps break the mud cake.
23. Back-washing could be used in aquifer overlain with stratum comprises silt, sandy clay or similar material.
24. Well development by jetting helps in breaking the mud cake deposited on the walls of bore hole.
25. A conventional centrifugal pump can be used for well development by jetting.
26. High-velocity jetting method is not suitable for development of wells drilled in layered, fine-grained or clayey aquifers.
27. Well development by fracturing method is suitable for alluvial formations.
28. Hydro-fracturing method of well development involves injecting high pressure air via the well into the formation.
29. Packers are used to seal off a section of the well.
30. The packers are usually first set near the top of the well.
31. Injection of liquified CO_2 into the aquifer freezes the water, opening nearby fractures.
32. Use of chemical agents in well development enhances the breakdown process of mud cake.
33. Chlorine is used to improve the yield in limestone formation.
34. The addition of polyphosphate to the water standing in the well helps considerably in the removal of mud while developing a well.
35. Cavity wells are developed by over-pumping.
36. In shallow wells, the yield is almost directly proportional to the drawdown.
37. A vacuum gauge installed on the suction side of the pump can be used to estimate the draw down in the well.
38. Water level during pumping can be measured by airline method.
39. Air line method can be used to determine drawdown in bore hole where the casing is connected to the suction side of the pump.
40. A vacuum gauge indicate the suction head from the centre of gauge.

Ans. True: 1, 2, 4, 8, 9, 12, 15, 16, 17, 19, 21, 22, 24, 25, 29, 31, 32, 34, 35, 37, 38, 40.

II. Select the correct answer.

1. The development of a tube well should be started from
   (a) bottom of screen (b) top of screen
   (c) middle of screen (d) bottom of casing pipe
2. Well development with air pressure is not suitable for
   (a) agricultural strainer (b) cavity well
   (c) gravel packed well (d) PVC strainer

3. Well development is more effective, when pumping is done
   (a) continuously (b) intermittently
   (c) half the design capacity (d) equal to the design capacity
4. In well development by surging with compressed air, the optimum working submergence should be about
   (a) 40 per cent (b) 50 per cent
   (c) 60 per cent (d) 70 per cent
5. The capacity of the air compressor required for each litre per minute of water at the anticipated pumping rate is about
   (a) 0.13 m^3/h (b) 0.18 m^3/h
   (c) 0.23 m^3/h (d) 0.28 m^3/h
6. Surging with surge block and bailing method of well development is not effective in tube wells with
   (a) PVC strainer (b) agricultural strainer
   (c) limited thickness of gravel pack (d) thick gravel pack
7. In well development by surging with surge block, surge plunger should be
   (a) above top of the well screen (b) bottom of the well screen
   (c) middle of the well screen (d) above the water table
8. Rawhiding is a method of well development by back-washing in which back-washing is done
   (a) by pumping (b) under pressure
   (c) with compressed air (d) under pressure and compressed air
9. Development of a cavity well is done by
   (a) jetting (b) surge block method
   (c) over-pumping (d) fracturing
10. The upper limit of pressure in jetting method of well development is
   (a) 10 kg/cm^2 (b) 15 kg/cm^2
   (c) 20 kg/cm^2 (d) 25 kg/cm^2
11. Acid treatment cannot improve the yield in
   (a) crystalline formations (b) limestone formations
   (c) dolmite formations (d) calcium carbonate formations
12. In hydro-fracturing, the packers are usually first set
   (a) near the top of the well (b) near the middle of the well
   (c) above the water table (d) near the bottom of the well
13. Following the development of a new tube well, it is tested to determine
   (a) aquifer parameters (b) yield and drawdown
   (c) type of aquifer (d) clogging of the aquifer
14. In tube wells the airline is used to measure
   (a) yield (b) aquifer parameters
   (c) specific capacity (d) drawdown

Ans. 1 (a) 2 (b) 3 (b) 4 (c) 5 (d) 6 (d) 7 (a) 8 (a)
9 (c) 10 (b) 11 (a) 12 (d) 13 (b) 14 (d).

7

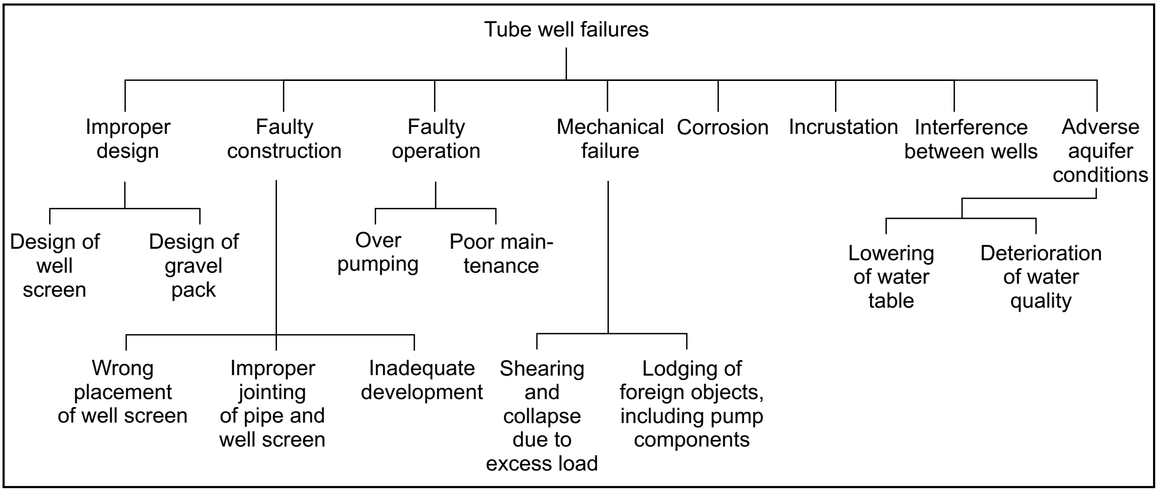
Rehabilitation of Sick and Failed Tube Wells

Tube wells are costly structures which require careful design, construction, operation and timely maintenance. A tube well should give trouble-free service if due care is ensured on these aspects. However, it has been experienced that a large number of tube wells constructed at high costs operate at very low efficiencies or fail completely. Tube well failures are generally indicated by either excessive sand pumping or steady decline in well yield. It may often be possible to rehabilitate the well by carrying out suitable remedial measures, though in certain cases (e.g. screen rupture, resulting in excessive sand pumping), even the costly operations may not be effective to restore the well. When such a stage is reached, the well is abandoned and a new well will have to be drilled.

Tube well failure may be due to inadequate design, faulty construction and operation, lack of timely maintenance and repair, and failures due to mechanical and chemical agents and adverse aquifer conditions. The main causes for tube well failures are categorised schematically in the accompanying chart.

7.1 EVALUATION OF WELL PERFORMANCE FOR DIAGNOSING CAUSE OF FAILURE

The likely cause of deterioration in a well can be traced from its performance study. The performance data, which covers the entire period of useful life of a well, will include water quality, pumping hours, well yield, variation in ground water level, and drawdown. The yearly observations will include collection of the record of pumping and inner depth of the well. Observations to be made twice a year (before and after the monsoon) include static water level, pumping water level, discharge and sand content after 2, 5, 10 and 15 minutes of operation. The water quality, to be determined every third year, will include the total dissolved solids, sulphates, bicarbonates, chlorides, silicon, iron, aluminium and calcium. This will also include the determination of magnesium, manganese, nitrate, flouride, sodium, *p*H, electrical conductivity and sodium adsorption ratio (SAR). Information on earlier treatments like redevelopment of well, acid treatment, or chlorine treatment for rehabilitation, if any, may also be collected. This may indicate reasons and details of treatment and the observations on well performance after applying the treatment.



The design and construction details of the well should always be available with the well owner or the organization responsible for its maintenance. They will include the year of construction, method of drilling, well log, depth of bore, aquifer materials (grain-size distribution curve, if possible), location, diameter and type of strainer and casing pipe, gravel pack material (design curve showing the grading of gravel pack used), method of well development, pump specifications, initial discharge, drawdown and sand content.

Based on the data collected over the service period of the well, performance graphs are drawn showing the variation of well discharge against time (Fig. 7.1) and increase in sand pumping against time.

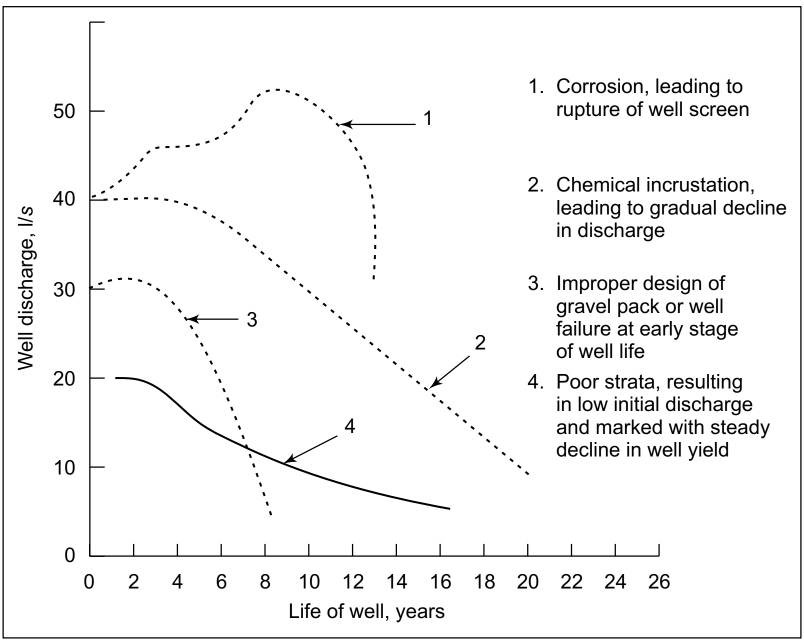


Fig. 7.1 Typical performance curves of sick wells for diagnosing the cause of failure

7.1.1 Trouble-Shooting

A careful study of the performance graphs of a well can identify the cause for its failure. The inferences are drawn on the basis of the following considerations:

(i) *Corrosion*

A sudden drop in the graph of well capacity versus time is an indication of failure of the tube well due to corrosion (Fig. 7.1). The other indication is increase in sand pumping, collapse of well screen and filling up of well with sand and gravel. Analysis of the well water will indicate the reasons for corrosion. Reduction in well yields, as a result of blockage of the screen slot openings, followed by structural rupture or collapse of screen, is a result of electro-chemical corrosion.

Pitting, due to corrosion, is indicated by air bubbles and fine sand pumping with water. There is also a reduction in well yield.

(ii) *Incrustation*

Chemical incrustation is indicated by a gradual reduction in the yield of the well (Fig. 7.1). However, it can also happen with a gradual lowering of the water table due to over-pumping or inadequate recharge. This can be verified by studying the behaviour of the water table over the service period of the tube well. Incrustation in the form of slime produced by iron bacteria, decreases yield of tube wells due to clogging of well screen and casing. This trouble could be identified from the fact that in this case the reduction in yield is somewhat rapid. Water quality analysis results are used to identify the type of incrustation.

(iii) *Improper Design of Gravel Pack and Well Screen*

Improper design of gravel packing is evidenced by sand pumping, right from the beginning of the operation of the well. This can also happen because of faulty design of well screen slots or wrong placement of the screen with reference to underground formations. Sand pumping results in the tube well filling with sand and sinking of the pump-house foundation. In such a case, a steep decline in well yield and early failure of the well takes place. The phenomenon can be verified from the well discharge versus time graph (Fig. 7.1).

(iv) *Inadequate Well Development*

This is indicated by the pumping of fine particles right from the time the well is put under operation. In this case, there is a gradual fall of gravel pack around the well, and need for regular gravel feeding.

(v) *Over-Pumping*

Over-pumping results in clogging of the surrounding formation, leading to a reduction in the specific capacity of the well. Sometimes, this may also cause rupture of the well screen.

7.2 INFLUENCE OF FAULTY DESIGN, CONSTRUCTION AND OPERATION ON WELL FAILURES

Well failures could often be attributed to basic design deficiencies, improper construction and lack of adequate attention in their operation.

7.2.1 Design Failures

The procedure for the design of tube wells, including screens and gravel pack, is presented in Ch. 4. As already discussed, the slot size of well screens to be installed in a particular area is designed on the basis of particle-size distribution of the aquifer material or gravel pack in case of strainer and gravel packed wells, respectively. Incorrect size of slots results in clogging of the screen, which leads to the reduction in well yield or continuous flow of sand with pumped water. Sand pumping may result in the formation of a cavity around the well casing or screen and sinking of the pump house, which may lead to the complete failure of the well.

Improper design of the gravel pack is one of the major causes of tube well failure. The size of the gravel is decided according to the particle-size distribution of aquifer (Ch. 4). Improper size of gravel pack results in sand pumping, which damages the pumps and leads to well failure. Sometimes, if the gravel is not uniformly distributed, bridging takes place, exposing some portions of the slotted pipe, which allow free flow of sand. Continuous flow of sand leads to cavity formation around the well, sinking of the pump house and extensive damage to the pump (Fig. 7.2).

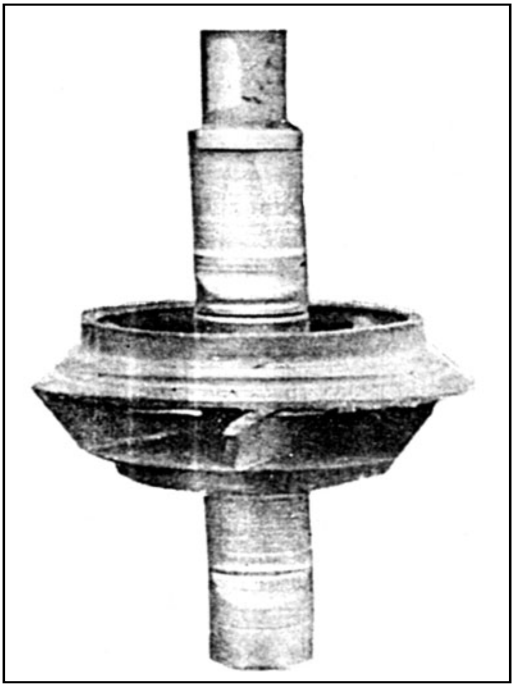


Fig. 7.2 Worn-out impeller and shaft of a submersible pump. Sand pumping due to the improper design of gravel pack has resulted in the excessive wearing and failure of the pump. (Village Mehmoodpur, Distt. Roop Nagar, Punjab)

7.2.2 Construction Defects

Faulty construction would include improper jointing of the casing pipe, screens and bail plug, wrong placement of well screens and deficiencies in well development. Improper jointing may result in pipe sections getting disconnected, thus allowing the formation material to get into the well.

The other construction faults are damage of well screen during lowering, and wrong placement of well screen due to inadequate sampling of strata during well drilling. The placement of the well screen in the well bore is important. Well screens placed incorrectly against silt or clay strata results in the continuous flow of fine particles. The overlying fine materials eventually settle down and get positioned against the screen perforations. Ultimately, the well fails.

If the well is not properly developed, it continues to pump sand along with water, resulting in reduction in well yield and damage to the pump. Often, excessive sand pumping may result in the formation of cavities around the screen and subsidence of the soil. Sometimes, gravel pack tube well may fail because of delay in development.

7.2.3 Deterioration of Envelop Material

Low cost well screens used in a shallow tube well are often affected by the deterioration of the envelop material, such as coir and nylon netting (Fig. 7.3). Biological products are far more susceptible to deterioration, compared to synthetic products. Use of nylon rope instead of coir and painting the steel frame to prevent rusting will prolong the life of such screens.

Well failure due to rupture of screens or casing could be avoided by careful design and construction. However, such wells are difficult to rehabilitate, once a rupture of a major magnitude has taken place. On the other hand, foreign objects lodged in a tube well can, in most cases, be extracted with the help of proper fishing tools.

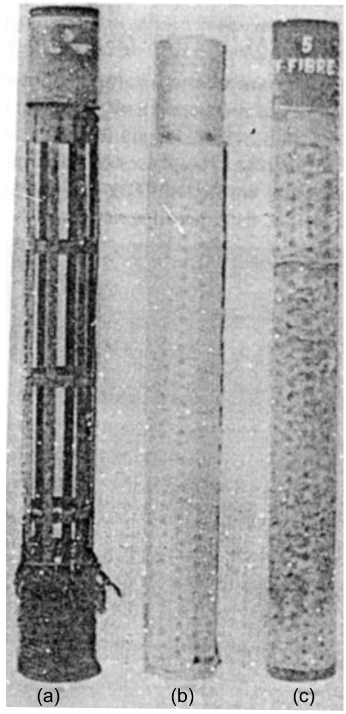


Fig. 7.3 Failure of envelopes over mild steel base pipes/frames in well screens for shallow tube wells: (a) Failed coir winding over mild steel frame after 3 years of use, (b) Initial condition of nylon netting over perforated mild steel pipe, (c) Netting is deteriorated after 6 years of use
Source: Institute of Hydraulics and Hydrology, Poondi, Tamil Nadu.

7.2.4 Faulty Operation

Faulty operation of a tube well includes over-pumping and lack of timely maintenance and repair. The pumping water level in a tube well should be kept above the level of the well screen. Lowering the water level below the top of the well screen has two major adverse effects: (i) The dewatered section of the screen no longer contributes flow to the well. Thus, the total flow into the well passes through a reduced volume of the aquifer. This increases the entrance velocity of water into the well through the screen (velocity of entrance should ordinarily be limited to about 3 cm/s). (ii) The dewatered portion of the screen allows aeration of the screen and the surrounding formation. This accelerates the oxidation of salts in the water and surrounding formation and their precipitation, resulting in the incrustation of the well screen.

Over-pumping results in the accumulation of fine particles adjacent to the well screen, causing clogging of the screen or surrounding water-bearing formation. It also promotes corrosion. Over-pumping results in excessive drawdown, which may cause differential hydrostatic pressures, leading to rupture of the well screen. Negligence in timely repair and maintenance may cause damage to the pump, the prime-mover or any tube well component, resulting in poor performance of the tube well. Operation at design capacity and timely repair and maintenance are essential to ensure the trouble-free service of a tube well.

7.3 PHOTOGRAPHIC EVALUATION OF WELL FAILURES

With the expansion of photographic technology, photographs can be produced to clearly show specific problems that might exist in a well. Study and evaluation of these photographs help in the selection of appropriate corrective measures. Well repair expenses can be significantly reduced if down-hole photographs are employed. The equipment consists of a bore-hole camera provided with a flash arrangement, which can be lowered into a tube well to take photographs (usually, stereo-photographs) at any depth (Fig. 7.4). Photographs may be made from black-and-white or colour films. Colour photographs have been used in uncased holes to identify formation materials. The best colour photographs of formation material are obtained in dry holes. However, colour photographs of bore-holes containing clear water can also be used for formation identification. Stereo-photographs of new wells provide a visual inspection of the entire well (Fig. 7.5). They suggest to the controlling agency and the well owner whether the well has been completed in accordance with guaranteed plans and specifications or not. However, the surveys cannot show detailed features of the grouting, gravel pack and screen placement versus formation changes. Photographic records of new wells can also be used for comparison with photographs taken on a later date, thus furnishing clues from which conclusions may be drawn for well rehabilitation. Well failures due to blocking by lost objects, including their precise location can be clearly identified by photographic surveys (Fig. 7.5(a)). This would suggest the type and design of fishing tool to be used or other remedial measures to be undertaken. Photographic surveys of wells subjected to chemical treatment against incrustation show the apparent effectiveness of the chemical rehabilitation of the well screen.

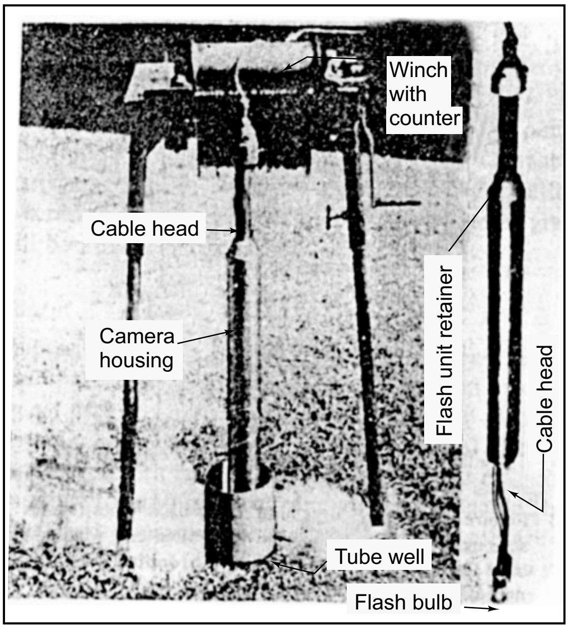


Fig. 7.4 View of a three-dimensional bore-hole camera unit showing details of parts

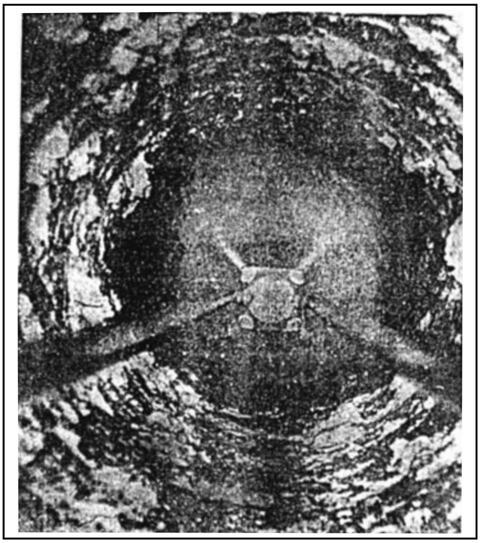


Fig. 7.5 Underwater view showing the inside of a screen tube well which is clogged by incrustation. Note the salt deposits blocking the slot openings of the well screen

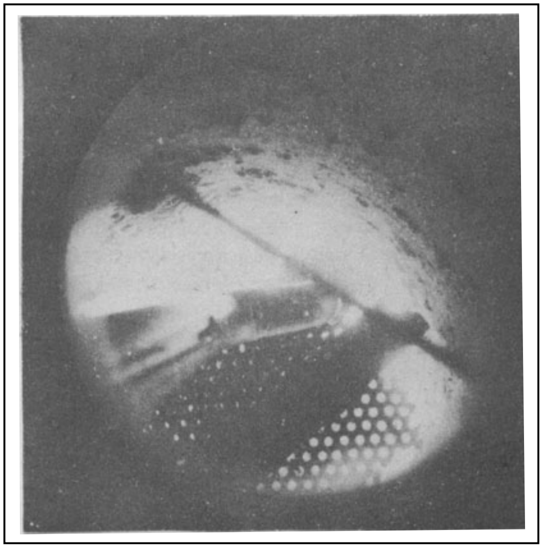


Fig. 7.5(a) Location of obstructions comprising a broken metal screen and steel rod obstructing a tube well at a depth as determined using a bore hole camera

A closed-circuit television system directly connected to the bore-hole camera system, though more expensive, if used for water well evaluation, has some advantages over stereo photographic surveys. Television equipment permit direct viewing of the condition of the well as the camera is progressively lowered into the well. Both vertical and horizontal viewing of the bore-hole is possible. An initial survey using a vertical-viewing probe is common, during which sections are noted where a horizontal view is desirable. When the initial survey is completed, the equipment is hoisted to the surface. The horizontal viewing mirror is attached to the cable and introduced into the well.

A problem in photographic and television well surveys is the absence of an acceptable method to rectify precipitated suspensions in water, particularly in old wells. The clarity of the pictures can be adversely affected or blocked out entirely by suspensions in the water, e.g. colloidal material, bacteria and algae clumps, and debris from corrosion or incrustation. Various precipitants and coagulants, such as alum, ferrous sulphite, etc., have been used occasionally to rectify the suspension, but with only limited success.

7.4 MECHANICAL FAILURES AND USE OF FISHING TOOLS

Mechanical failures may occur in tube wells due to blocking by foreign objects, including component parts of drill rod and tools, pumping sets, tools, wires, stones or other objects which accidently fall into the well. Rupture of casing pipes and well screens may occur at joints or other places, due to inadequate structural strength. Non-metallic pipes (rigid PVC or fibre glass) could get damaged due to abrasion with the metallic parts of pumps which may be forced against it while lowering the pumping set in a crooked well or fishing out pump components for rehabilitating a blocked well. In corrosive waters, the column pipe joints and pump parts may get progressively weakened due to corrosion, get disconnected and fall into the well.

Unscrewed joints are a common cause of mechanical failure of tube wells. These can be avoided by proper matching of the box and pin components of the joints. The pin shoulder and box face of joints should be thoroughly cleaned. It should be ensured that they are free from imperfections which prevent full and uniform contact. The threads and shoulders are coated with a light machine oil before joining. The joints are firmly made, but excessive pressure is avoided to prevent breakage of boxes and pins.

In case of all forms of accidents, prevention is better than cure. Therefore, it is essential to exercise care and attention at all times in construction, operation and maintenance of tube wells. However, inspite of care, sometimes foreign objects may fall in the tube well. The first step in their removal is to locate them in relation to their position and orientation. This is followed by their removal through proper fishing tools.

7.4.1 Impression Block

An impression block is used to obtain an impression of the top of the object before attempting any fishing operation. Impression blocks are of many forms and design. Figure 7.6 illustrates an impression block made from a block of soft wood turned on a lathe. The diameter of the block is 2 cm less than that of the drilled hole. The upper portion is shaped in the form of a pin and driven to fit tightly into the box collar of a drill pipe. To ensure further safety, the wooden block is tied with wire or pinned securely to the collar. Alternatively, the block could be fixed to a bailer. A number of nails are driven to the lower end of the block with about 1 cm of it projecting out. A sheet metal cylinder of about 5 to 7 cm is temporarily nailed around the block to hold molten wax, which is poured into it. Warm paraffin wax, soap or other plastic material poured into the cylinder is left to cool and solidify. The metal cylinder is then removed. The nail heads hold the plastic material to the block. To locate the position of a lost object, the impression block is carefully lowered into the hole until the object is reached. After a proper stamp is ensured, the tool is raised to the ground surface, where the impression made in the plastic material is examined for identifying the position of the lost object and designing or selecting the right fishing tool.

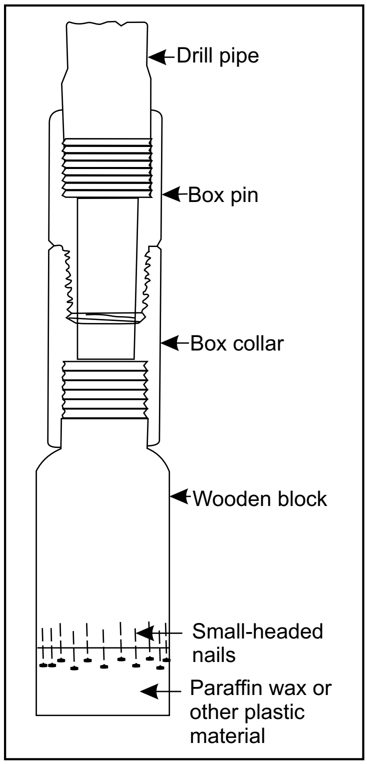


Fig. 7.6 Impression block made of soft wood. *Adapted from:* Gibson and Singer (1969)

7.4.2 Fishing Tools to Recover Objects Lost in Tube Wells

The term 'fish', as used in tube well technology, describes a well drilling tool, pump component or other foreign body accidently deposited or stuck in bore-holes and wells. The type of fishing tools required for a specific job will depend on the object to be lifted and the position in which it is laid. It may often be necessary to design a tool to suit a particular job. However, series of fishing tools (Figs 7.7 to 7.9), suitable for different jobs are available and could be adapted or modified to suit a particular requirement.

Inventory of Well and Pump Components

To ensure the use of the right tool in a fishing job, it is desirable to keep a record of the dimensions and locations of all that is used in a tube well structure or pumping set. All tools brought to the well site are accurately measured and recorded.

7.4.3 Common Fishing Jobs and Tools

While fishing jobs can be classified into various groups, individual jobs within each may vary greatly. Hence, the skill and ingenuity of the operator plays a major role in the success of a fishing operation. Some common types of fishing tools are discussed in the following sections:

Tools to Recover Lost Drill Rods

Tapered Fishing Tap. A tapered fishing tap (Fig. 7.7 a) is used to recover drill pipes broken off and fallen into the drill hole It is effective if the top of the drill pipe is unobstructed by the settling of the drill cuttings. An impression block may be used to identify the condition of the parted drill pipe. The tool is made of heat treated steel. It tapers approximately 1 cm in every 12 cm, from a diameter somewhat smaller than the inside diameter of the coupling to that equal to the outside diameter of the drill stem. The tapered portion is threaded and fluted the full length of the taper to permit the escape of chips cut by the tap. It operates like a machine tap, cutting its own threads when rotated and making a connection with the drill pipe. The tap is lowered carefully until it engages the lost pipe. It is turned slowly by the rotary mechanism or by hand, until it is threaded into the pipe. A controlled supply of drill fluid is maintained during the operation.

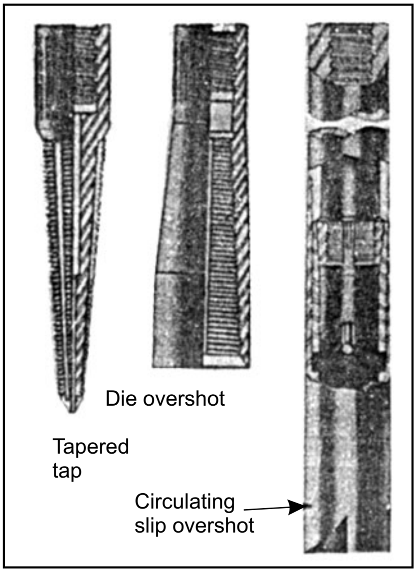


Fig. 7.7(a) Fishing tools for parted drill pipes *Adapted from:* U.S. Dept of the Army Manual TMS—297 (Anon;. 1957)

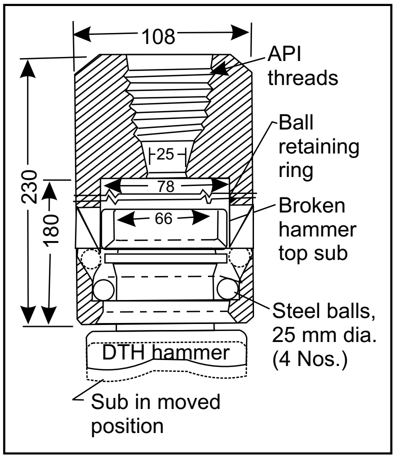


Fig. 7.7(b) Fishing tool for the recovery of down-the-hole hammers Tech. *Note:* All dimensions in mm

Die Overshot (Figs 7.7 a). This tool is also used to fish out lost drill pipes. It is a long tapered die made of heat-treated steel designed to fit over the top end of the lost drill pipe and cut its own threads as it is rotated. It is fluted to permit the escape of metal cuttings.

Circulation Slip Overshot (Fig. 7.7 a). It is a tubular tool, about 1 m long, with inside diameter slightly larger than the diameter of the drill rods. The bottom is belled out and has a notch to add the tool to centre and slip over the lost drill pipe. It tightens against the pipe when the slip is pulled down into the tapered sleeve and the tool is raised.

Miscellaneous Fishing Tools

The miscellaneous fishing tools commonly used are given in Figs. 7.8 and 7.9.

Latch Jacks (Fig. 7.9). These are used to fish lost bailers or any tool that has a loop or 'eye' in which the latch may be caught.

Horn Jackets (Fig. 7.9). These are used for recovering tools lost down the bore. The horn jacket is driven over the lost tool. It secures the tool with a friction grip.

Spuds (Fig. 7.9). Spuds are used for drilling around and loosening tools which are stuck in the hole and cannot be moved with ordinary fishing tools.

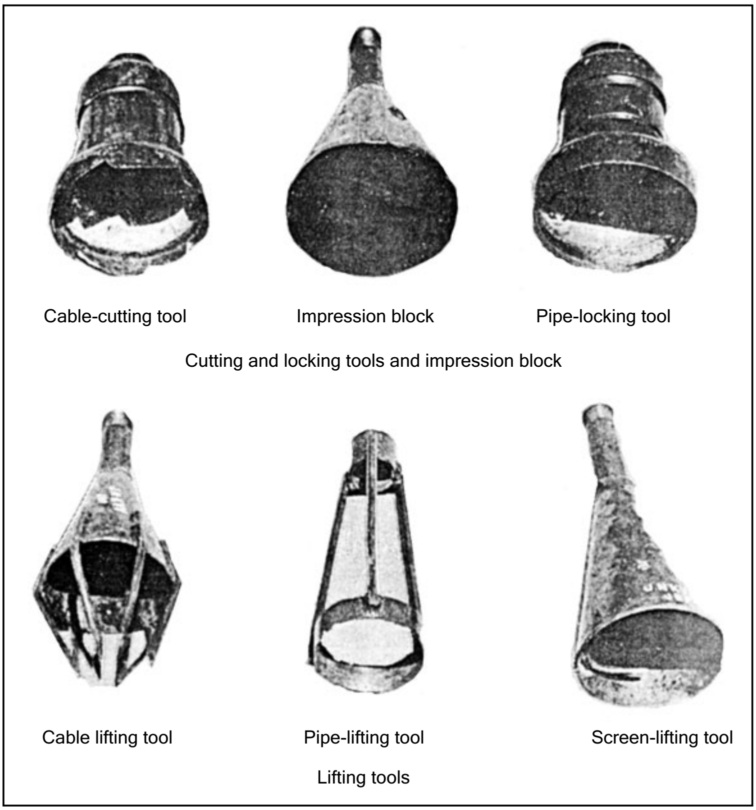


Fig. 7.8 Indigenous fishing tools for tube wells
Courtesy: ICAR Coord. Res. Project, J.N.K.V.V., Jabalpur

Rope Spear (Fig. 7.9). It is used to fish broken rope from the bore. The tool consists of a single prong with a number of upturned spikes projecting from it. The spikes have sharp inside corners to catch even a single strand of wire. If the lost tools are stuck in the hole and cannot be pulled, the sharp spikes will shear the wire line. The shoulder of the spear should be about the same size as the bore hole, in order to prevent the broken wire line from getting past the spear as it is lowered, and causing it to become stuck in the hole.

Bumper. A bumper jar (Fig. 7.9) is used for loosening tools which are struck in the bore hole or well casing, but are still attached to the hoist line of the drilling equipment.

Under-reamer (Fig. 7.9). It is used to ream holes to size for the casing to follow.

Spear casing (Fig. 7.9). It is used for jarring the casing at the bottom or extracting a casing that is lost or broken in the bore-hole.

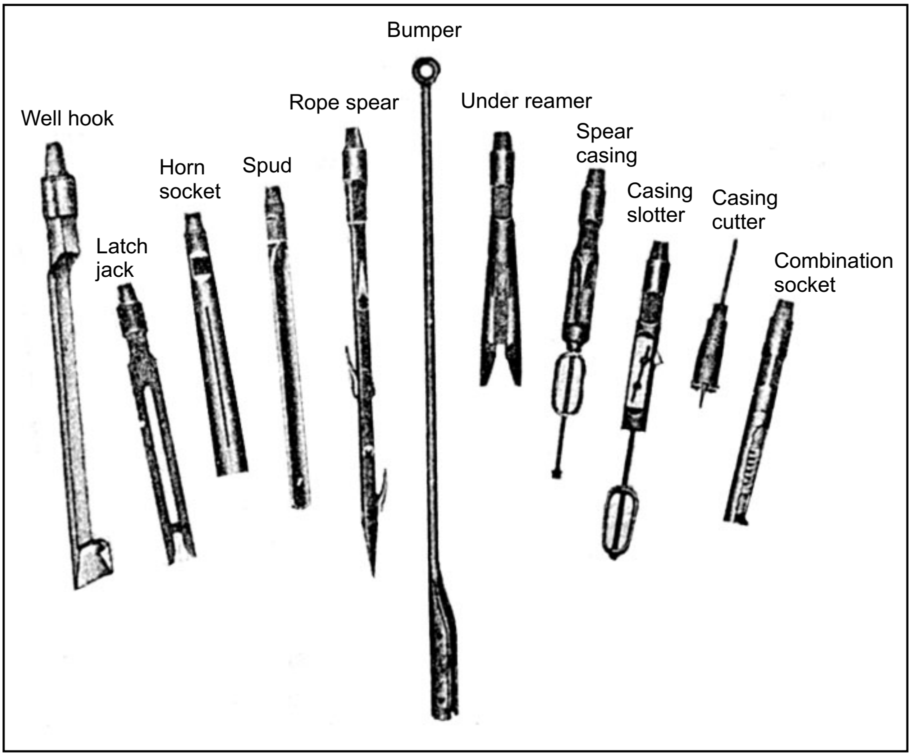


Fig. 7.9 A set of common bore-hole fishing tools
Courtesy: Hardwood Bagshaw Engineering Ltd.
Edwardstown, Australia

Casing slotter (Fig. 7.9). Casing slotters and casing cutters are used for cutting slots in casings when positioned opposite water-bearing formations.

Combination socket (Fig. 7.9). It is used to recover tools which have been unscrewed or got lost due to the pipe breaking at the swivel. It is provided with two sets of slips, one used to engage the threads of the pin on a bit, stem or other tool, and the second to hold the neck of the rope socket. A proper set of slips must be selected for the particular fishing job, in accordance with the knowledge of the exact size of the fish.

Well hook (Fig. 7.9). When the top of the lost tool has fallen into a cave inside the bore hole, the well hook is the most efficient fishing tool for realigning so that the socket can be used. This is done by running the tools at moderate speed, allowing the jars to hit both up and to the tip of the tool.

7.5 CORROSION AND INCRUSTATION OF WELL SCREENS

Yield reduction in tube wells constructed according to accepted standards are usually attributed to corrosion or incrustation. A large number of tube wells are abandoned every year due to failures caused by corrosion and incrustation. Corrosion is a chemical attack on any material, which changes its form or breaks it down. In other words, it is the gradual destruction or 'eating away' of the material. It is a common cause of failure of buried metallic pipes and mild-steel tube wells. Incrustation, on the other hand, is the accumulation or deposition of extraneous materials. As applied to tube wells, incrustation is the clogging or stoppage of the well screen and the surrounding water-bearing formation. It results in the accumulation of material in and around the openings of the screen or in the voids of the water-bearing formation.

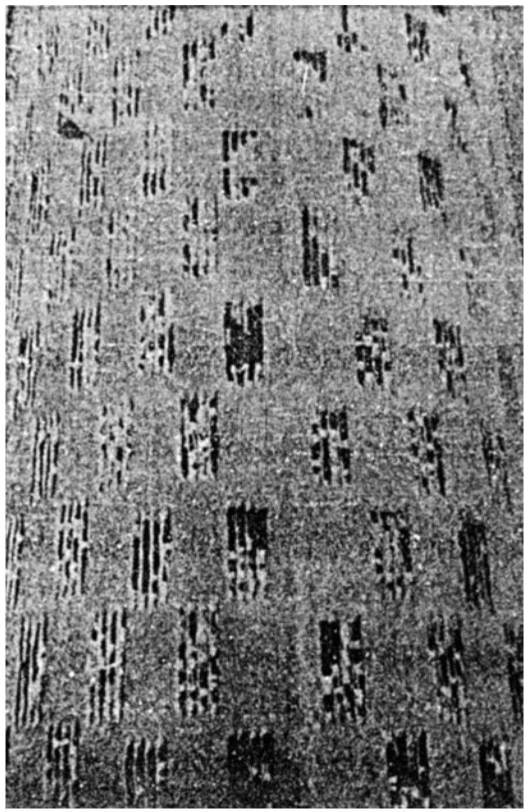


Fig. 7.10 Corrosion and incrustation in a mild steel well screen. The large openings formed by corrosion result in sand pumping and ultimate collapse of the well. Incrustation has blocked many of the slot openings.
Courtesy: Mohandass (1982)

7.5.1 Corrosion

Corrosion may be defined as a chemical action on the well casing or screen, exerted by outside factors and resulting in the erosion of the metal. Corrosion can severely limit the life of tube wells in the following ways:

1. Screen-slot openings get enlarged, resulting in the loss of metal and sand pumping (Fig. 7.10). This leads to the entry of sand and gravel and the eventual blockage of the tube well.
2. The strength of the screen and casing get reduced, resulting in their collapse.
3. The yield of the well is reduced by redeposition of corrosion products on the well screen, thereby causing blockage of screen slots.
4. Pump components get corroded, resulting in screen damage (Fig. 7.11).

Causes and Forms of Corrosion

Metals are corroded due to many reasons, under various conditions, and at different rates. The main agents causing corrosion, either singly or in combination are air, soils, acids, oxidising agents, natural water, brines, organic compounds, high temperatures, sulphur compounds and alkalies. In general, ground water can be considered corrosive under the following conditions:

1. The *p*H is less than 7.0 (As *p*H decreases, corrosion activity increases)
2. Dissolved oxygen exceeds 2 ppm
3. Total dissolved salts (TDS) exceeds 1000 ppm (mild steel in water with high TDS is liable to corrode severely. Hardened surfaces corrode faster than annealed).
4. Electrical conductivity is greater than 1.5 dS/m
5. Dissolved carbon dioxide exceeds 50 ppm
6. Chloride content of water exceeds 300 ppm
7. High velocity of entrance of water into the well screen and high velocity of water inside the casing pipe
8. High temperature (corrosion rate doubles for every increase in temperature of 22°C)
9. Presence of hydrogen sulphide in excess of 1 ppm
10. Presence of sulphur dioxide or similar gases

The following are the different types of corrosion in well screens:

1. Direct chemical corrosion
2. Galvanic or bi-metallic corrosion
3. Microbiological corrosion
4. Dezincification
5. Graphitization
6. Concentration/solution cell corrosion
7. Pitting or localised corrosion
8. Fatigue or corrosion cracking

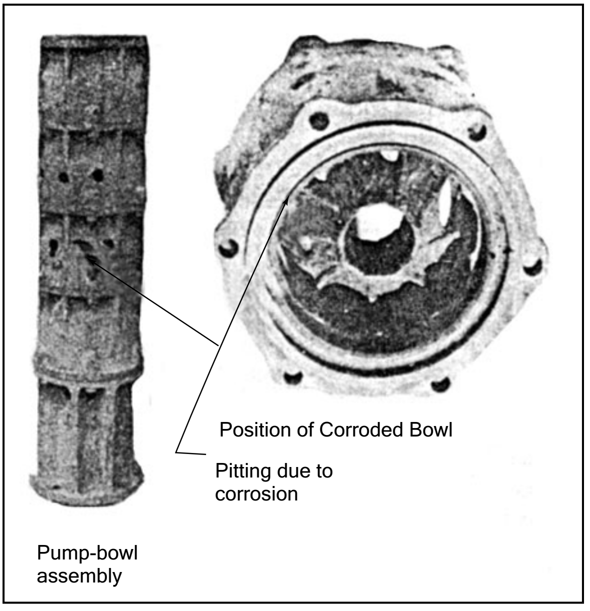


Fig. 7.11 Submersible pump severely damaged by corrosion
Courtesy: Mohandass (1982)

Direct Chemical Corrosion

This is an electrochemical phenomenon involving oxidation, resulting in the loss of electrons and ionization of the metal. The chemical reaction and electron release lead to other reactions such as rust formation. Direct chemical corrosion results in the uniform loss of metal, with occasional perforation in some areas.

Increasing the rate of flow of corrosive water across a metal surface intensifies corrosion by supplying more reactants and removing the protective reaction products or films. In addition, variable velocity along a metal surface can establish electrolytic corrosion cells by changing the concentration of reaction products from point to point. Rapidly moving water can cause cavitation effect in relatively low-pressure areas, resulting from flow diversion or rotation as in pump impellers.

The characteristics of the soil influence corrosion substantially. Poor aeration, high acidity, low EC and high salt and moisture contents are characteristics of corrosive soils. The most corrosive soils are muck and peat. Presence of chlorides and sulphates in soils increases the corrosion rate of ferrous and some non-ferrous metals.

Galvanic Corrosion

Whenever two different metals are electrically connected in a conducting solution, galvanic corrosion results due to their forming an electrolytic cell. The section of the cell being corroded is the anode, and the section on which the protective coat is being formed is the cathode. A well screen made of two different metals is readily damaged as a result of galvanic corrosion. The rate of corrosion is influenced by: (1) the scour action of the electrolyte as it passes over the surface being corroded, (2) the relative size of the anode and cathode, and (3) the corrosion-resisting properties of the metal involved.

Microbiological Corrosion

Sulphur and carbon, when present in soils, are attracted by bacteria and form acidic products which increase corrosion. The microbes causing severe corrosion are sulphate-reducing anaerobic bacteria which reduce the sulphates present in the soil or in water and convert metallic ion into the sulphide. Bacteria thrive well in poorly drained soils rich in organic matter and containing sulphates. The optimum range in *p*H for bacterial corrosion is 5 to 9.

Dezincification

Dezincification is sometimes called selective corrosion. It is essentially the removal of zinc from a bimetallic alloy containing zinc (e.g. brass). The residue left behind is weak and porous. It results from the electro-chemical difference in potential between the metals in the alloys. The most favourable conditions for dezincification are the presence of a good conducting solution, such as brine or slightly acid condition, dissolved oxygen and a two-metal alloy. Dezincification may sometimes cause sudden failure of pipes or even the pump, which may otherwise appear structurally sound.

Graphitization

Graphitization is also a selective corrosion process. Graphitization of low-carbon steel and cast iron is an electro-biological process in the anaerobic condition. It is usually associated with the presence of sulphate-reducing bacteria in the well.

Concentration/Solution Cell Corrosion

Differential oxygen concentration at different points of a casing pipe causes long cell action, resulting in corrosion at the less aerated zone. Differences in oxygen concentration can be caused by variations in the composition and compaction of different layers or sections of the soil, and in the movement of air and water in the soil by buildings or vegetation.

Pitting or Localised Corrosion

Pitting is defined as the formation of small holes in the blind pipe, positioned between the static water level and pumping water level, by the oxidising action of air and the corrosive action of ground water. This results in a considerable decrease in well discharge.

Fatigue or Corrosion Cracking

Fatigue is caused by alternating stresses set up by vibrations or other periodic mechanical changes occurring in the pipes or pump. Fatigue, combined with corrosive water, causes cracks in the casing pipe. Cracks develop along the line of stress concentration.

When iron (Fe) corrodes in water, iron atoms are converted to ferrous ions upon the loss of electrons,

$$Fe \rightarrow Fe^{++} + 2e^- \quad (7.1)$$

where, e^- denotes an electron

The ferrous ions then combine with hydroxyl ions to form insoluble ferrous hydroxide

$$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2 \quad (7.2)$$

$Fe\,(OH)_2$ eventually gets oxidised, through contact with oxygen, to the commonly observed red iron rust. Hydroxyl ions are formed by either of the following reduction reactions:

$$H_2O + \frac{1}{2}\,O_2 + 2e^- \rightarrow 2OH^- \text{ (neutral or alkaline medium)} \quad (7.3)$$

$$2H^+ + O_2 + 4e^- \rightarrow 2OH^- \text{ (acid medium)} \quad (7.4)$$

Thus, the corrosion process is largely an electro-chemical destruction of the metal. Oxygen in the oxidising agent often accelerates corrosion. In some cases, however, corrosion may be reduced or eliminated by the oxidising agents, if they are capable of forming protective films on the metal surface.

Corrosion Resistance of Metals and Alloys

Metals and their alloys vary greatly in their resistance to corrosion. The important properties of metals which influence the extent of corrosion are their chemical affinity, oxidation property, the properties of corrosion by-products, composition of the metal, original state of the metal surface and the galvanic relationship of two or more metals in an alloy. The order of some of the metals with tendencies to corrode is as follows:

Magnesium
Aluminium
Cadmium
Steel and iron
Lead
Tin
Brass
Copper
Stainless steel

In the above list magnesium has the least resistance against corrosion and stainless steel the highest.

Protecting Well Screens Against Corrosion

While installing a new tube well, one should determine the conditions under which the screens are to be operated and the type of corrosion anticipated. Adequate protective measures against corrosion should be provided in the design and management of a tube well. A mild steel well screen is liable to be corroded quickly under saline ground water conditions. Hence, wherever possible, corrosion resistant material should be used for well screens in corrosive ground water. Rigid PVC pipes, fibre-glass reinforced plastic pipes, stainless steel pipes and pipes made of metal alloys like zinc-free bronze are used to overcome the problem of corrosion of well screens. Asbestos-cement pipes can also be used successfully in corrosive ground waters. However, its use is limited to very shallow tube wells due to its poor tensile strength.

Under corrosive conditions, well screens should be designed with large open areas so as to reduce the entrance velocity of water. The thickness of the casing pipe and screen should be comparatively large. Keeping in view the factors accelerating the process of corrosion, various management steps like decreasing the rate of pumping or decreasing the drawdown could be taken.

Corrosion-Resistant Paints and Coatings

Painting of mild steel pipes with anti-corrosive paints greatly reduce corrosion. Some commonly used paints/coatings to reduce corrosion are aluminium, asphalt, red lead and coal tar. However, paints have the disadvantage of forming scales on the metal surface. The scales are subsequently removed by the flowing water. Hence, the effects of the paints do not last long.

Cathodic Protection of Mild Steel Tube Wells in Corrosive Ground Water

The principle of cathodic protection of tube wells may be explained as follows:

Whenever two different metals are connected together in a conducting solution, the electric current set up due to the metals forming an electrolytic cell causes galvanic corrosion. The section being corroded is the anode and the section on which deposition takes place is the cathode.

The following are the two methods of applying cathodic protection against corrosion of mild steel pipes and other objects:

(i) Impressed Current

In the impressed current method, electric current is passed from a direct current source, through anodes buried in the soil some distance from a mild steel pipeline or other structure which is susceptible to corrosion. The current flow is from the anodes, through the soil or water, to the pipe which serves as the cathode, and back to the anode. The impressed current method is used extensively in protecting mild steel pipelines in water supply projects. However, its applicability in tube wells has not yet been established.

(ii) Sacrificial Anode

In case of the sacrificial anode system of cathodic protection, a metal of higher negative potential than that of the material of the pipe to be protected is used as the anode. The metal pipe acts as the cathode and the intervening water as electrolyte (Fig. 7.12), thus establishing the flow of electrons from the anode to the cathode. During electrolysis, the anode gets dissolved slowly and the metal ions in the solution are deposited

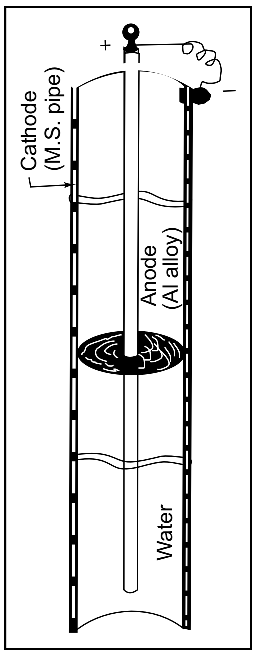


Fig. 7.12 Note electrolytic cell formed by the sacrificing anode immersed in water in acidic range in the tube well. The well pipe acts as the cathode

at the cathode. Thus, the main pipe is protected from corrosion by sacrificing the metal of the anode. Magnesium has the largest negative potential in the electrochemical series and is often used in water-supply pipelines where the resistivity of the soil is high. Aluminium and zinc anodes are employed in soils of lower resistivity, and saline water. Sacrificial anodes are easy to install and no power costs are involved, as compared to the impressed current method. They are effective in prolonging the service life of mild steel tube wells in corrosive water. However, the anodes have to be replaced periodically at the end of their useful life.

The anodes may be made of magnesium, zinc, aluminium, tin or their alloys. They are commercially available in diameters ranging from 1.5 to 8 cm and lengths of 1 to 3 m. Research findings of the ICAR Coordinated Project Centre on Wells and Pumps at the Gujarat Engineering Research Institute, Vadodara, have established the adaptability of aluminium-zinc-tin alloy in the cathodic protection of tube wells (a commonly used alloy has Al 90%, Zn 7% and Sn 3%). Alloys cast in steel core pipes of 1 cm diameter are also available. The anode rods are threaded at their ends for jointing with each other through sockets or couplings.

Figure 7.13 illustrates the installation of anodes for the cathodic protection of tube well. The anodes are lowered to extend to nearly the entire depth of the wells. They are joined with 2.5 cm diameter

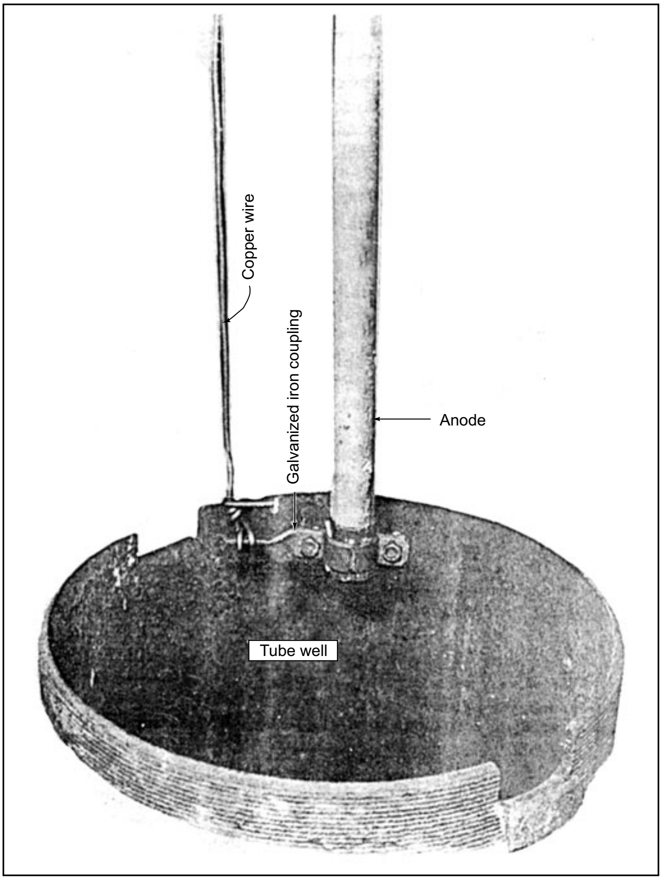


Fig. 7.13 Lowering of anode into a tube well for cathodic protection

galvanized iron couplings. To prevent breaking away of the anode due to corrosion, each coupling is joined together by a copper wire of 4 mm diameter, with the help of a clamp which is provided with 'eye hole' for passing the wire. Thus, all the anodes are joined into a continuous line and suspended in the well, from its top, with the help of the copper wire. The couplings and the copper wire, being made of metals with better corrosion resistance than the anode, are retained in their original form, while the anodes gradually disintegrate due to corrosion (Fig. 7.14). Hence, this arrangement permits the removal of the anode assembly periodically for replacement of the corroded anodes. In order to complete the electrical circuit, the anode assembly and the casing pipe (cathode) are connected together by a copper wire at the top of the well.

The life of anode will depend on the diameter and depth of the tube well, the composition of different metals forming the alloy of which the anode is made, the resistivity of the ground water and the resulting electrical potential. A potential of 0.85 V is considered adequate for the protection of a mild-steel tube well against corrosion. Thatte *et al.* (1983) recommended that the ratio of the surface area of an Al-Zn-Sn anode to that of the mild steel cathode (well casing and screen) should be 1 : 20 (only the area below the static wear level in the well is considered). They observed that about 17 kg of anode will prolong the life of a 100 m deep tube well of 21 cm diameter by one year. The anodes above the water surface in the well are unaffected by corrosion and could be reused while replacing the corroded anode below. The corroded anodes can be remoulded, with a loss in weight of about 20 per cent, and used again.

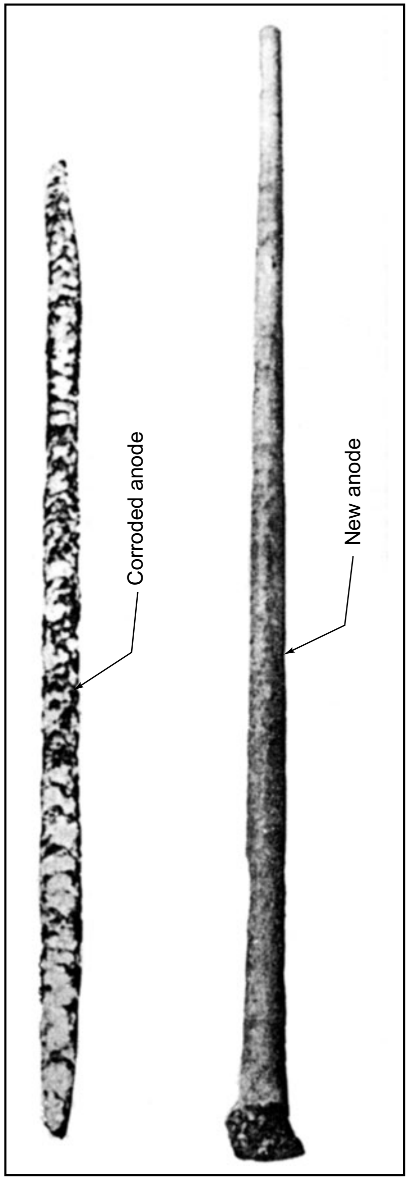


Fig. 7.14 Samples of new and corroded anodes used in cathodic protection of tube wells

7.5.2 Incrustation

Incrustation is one of the common troubles encountered in tube wells. It is mainly due to the poor quality of ground water. Incrustation may be defined as the clogging of well screens or water-bearing formations due to salt deposits. The deposits are generally hard, brittle and cement-like, though they may sometimes be soft and gummy. They clog the screen openings (Fig. 7.15) and the pores of the aquifer, due to which the yield of the well is reduced greatly. Incrustation is a property of the water. Therefore, the material of the pipe does not play a direct role in its occurrence.

Incrustation could be of different types, based on the material responsible for its occurence. These materials include dissolved substances in water recharged to the aquifer, mineral metals and the ion exchange reaction of water with the aquifer material. In general, incrustation may be either soft or hard. Soft incrustation is the result of carbonates forming light, fluffy deposits or sticky, pasty sludge which are relatively easy to remove. Hard incrustation is the result of water-soluble sulphates and is more difficult to remove.

Water is expected to be incrustive under the following conditions:

(i) *p*H value is above 7.5
(ii) Carbonate content exceeds 300 ppm
(iii) Iron content exceeds 2 ppm
(iv) Manganese content exceeding 1 ppm coupled with high *p*H.

The following are the main processes and agencies causing incrustation:

1. Precipitation of the material contained in the ground water and carried into the well screen in solution. Precipitation of salts may also result from the lowering of pressure in the vicinity of the well and exposure of the well screen to air. (The chief incrusting agents are carbonates of calcium and magnesium. They cement the sand grains together).
2. Deposition of suspended material like silt and clay on the well screen.
3. Presence of iron bacteria in ground water. The screen openings and formation voids get filled with a jelly-like colloidal substance which turns hard on exposure to air.
4. Presence of slime-forming organisms other than iron bacteria. These organisms feed on ammonia and dead or decomposing organic matter. (In most cases, however, there is no organic matter in deep water-bearing formations).

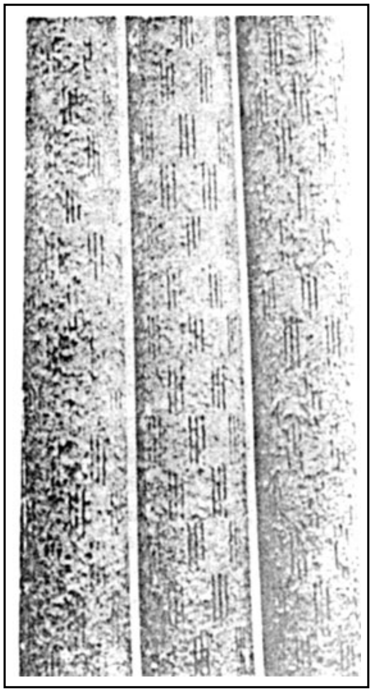


Fig. 7.15 Incrustation in mild steel slotted pipe well screens. In the pipe sections on either side, most of the slots are blocked by incrustations, while in the central pipe the incrustation is only partial

Different Forms of Incrustation

The following are the different forms of incrustation, in order of their frequency of occurrence:

(i) Precipitation of Carbonates, Sulphates and Silicates of Calcium and Magnesium

Calcium carbonate is one of the most extensively found materials in ground water. The solubility of calcium carbonate depends upon the quantity of free carbon dioxide in water. This is a function of the *p*H of water and its temperature and pressure. A low-pressure zone is developed around a well as a result of pumping, and some of the dissolved carbon dioxide is released from solution. Some calcium bicarbonate is then reconverted into calcium carbonate which is deposited as a cement-like material on the well screen. This deposit may sometimes extend to the water-bearing formations around the well. In addition to the sand grains around the well, which are cemented together, other minerals like iron compounds, aluminium silicates and organic materials may also get entrapped in the carbonate deposits. Sometimes calcium carbonate may be present in very small quantities, yet its presence plays a vital role in incrustation as it acts as a basic binder. This type of deposit is responsible for about 90 per cent of the cases of incrustations in tube wells.

(ii) Precipitation of Compounds of Iron and Manganese

When iron and manganese salts are present in ground water, the increase in flow velocity in the vicinity of the well upsets the salt balance and precipitate insoluble iron and manganese hydroxide. They ae jelly-like and fluffy. Oxidation can then take place due to the dissolved oxides in water and these are transformed into hydrated oxides. Ferric oxide is reddish brown, like common rust, while hydrated ferrous oxide is black sludge. When ferrous bicarbonate come in contact with oxygen, it gets oxidized to form insoluble ferric hydroxide:

$$4Fe(HCO_3)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 + 8CO_2 \tag{7.5}$$

Water table wells are more susceptible to oxidation as air can get into the zone of daily depletion of the water table, because of their intermittent working, and oxidise the salts there. The sand particles of the water bearing formations get progressively coated with iron oxide, which reduces the void space of the aquifer. The reduction in void space reduces the storage capacity of the aquifer.

Incrustation resulting from manganese salts is less frequent. Soluble manganese bicarbonates are converted into insoluble manganese hydroxide as a result of their reaction with oxygen. It precipitates as a dark-brown deposit.

(iii) Slime-Clogging Produced as a Result of Iron Bacteria or other Slime-Forming Organisms

Iron bacteria are grown as a result of the release of carbon dioxide, deficiency of oxygen, and darkness. The bacteria convert dissolved iron into the insoluble ferric state, which forms a slime that clogs the screen slots and pores of the aquifer. This may grow in water pipes and may clog them (Fig. 7.15).

(iv) Mechanical Incrustation

Mechanical incrustation may take place because of deposits of silt and clay in the slots of well screens. This may be due to inadequate development of the tube well or faulty design of the well screen.

Diagnosing Incrustation Problem

Chemical incrustation is indicated by a gradual reduction in yield of the well. However, it can also happen with a gradual lowering of the water table due to over-pumping or inadequate ground water recharge. This fact can be verified by studying the behaviour of the ground water level over the service period of the tube well. Incrustation in the form of slime produced by iron bacteria decrease well yield due to clogging of the well screen and casing. This trouble can be identified from the performance curves of the well. In this case, the reduction in well yield is somewhat more rapid. Water quality analysis are used to identify the type of incrustation.

Rehabilitation of Incrustated Tube Wells

Careful consideration should be given to all methods of preventing or retarding incrustation. However, in a large number of cases, incrustation will occur sooner or later so that well treatment becomes necessary. The following are the management procedures usually adopted to reduce incrustation in tube wells:

1. The drawdown while pumping should be kept as small as possible. This will control the release of carbon dioxide so that precipitation of carbonate in the well screen is kept in check. This can be done by reducing the pumping rate and thereby increasing the pumping period.
2. Well screens, in regions with poor quality ground water, should be so designed that the entry of water is met with the least possible resistance. Hence, screens having large areas of opening and fully penetrating the aquifers should be installed. This will result in low entrance velocities, leading to retardation in precipitation of iron salts and carbonates. Care in the development of a well will also reduce incrustation.
3. While planning ground water development of an area, efforts should be made to spread the pumping load by designing a large number of low-capacity wells rather than a few large-capacity wells.
4. Well screens should be cleaned periodically, whenever local experience indicates the possibility of reduction in well yield because of incrustation. This can be achieved by redeveloping the well at intervals of one or two years, or by acid treatment.

When the well performance is observed to have deteriorated, in spite of preventive measures, because of incrustation, suitable rehabilitation procedure should be adopted. Depending upon the cause of incrustation, such wells can be treated by applying hydrochloric acid, sulphamic acid, glassy phosphates, chlorine, etc. Acid treatment is effective in removing carbonates. However, when calcium and magnesium silicates or sulphates form the basic binder, they are not treated by the acid treatment method as acid has no action on them. Glassy phosphates are effective in removing iron and manganese. They also help to remove silt and clay. Bacterial growth and slime can be removed by chlorine treatment.

Hydrochloric Acid Treatment

Carbonate-type incrustation is removed by hydrochloric acid treatment. Concentrated hydrochloric acid of commercial grade (28% strength) is usually used in well treatment. It should contain a suitable inhibitor which helps in the quick dissolution of calcium and magnesium carbonates. It also slows down the acid attack on mild-steel well casings. Hence, the possibility of any damage to the pipe during treatment is minimised. If inhibited acid cannot be obtained, a home-made inhibitor can be used. A solution of about 0.7 kg of gealtine in warm water, added to 100 litres of acid is usually adequate.

Treatment Procedure. The arrangement of equipment for hydrochloric acid treatment is shown in Fig. 7.16. It consists of a 2-2.5 cm diameter plastic pipe which is long enough to reach the bottom of the well. The pipe, supported by suitable clamps, is lowered into the well. The upper end of the pipe is provided with a funnel inlet and overflow arrangement with a T-joint. The overflow takes care of any sudden blow out.

A solution of hydrochloric acid is prepared as indicated above. The acid solution required for one treatment should be 1.5 to 2 times the volume of water in the screened portion of the well. Sufficient acid is poured into the well to fill the bottom 1.5 m depth of the screen. The acid-feeding pipe is then raised to about 1.5 m and more acid poured. Even though acid is heavier than water and will displace it, the two will mix readily when stirred and the acid becomes easily diluted.

The effectiveness of acid treatment depends upon the contact between the chemical and the deposits on the well screen as well as in the adjacent aquifer. Chemical penetration will follow the path of least resistance. Hence, it is difficult to treat a clogged aquifer. It is, therefore, essential to agitate the acid solution vigorously and to surge it with a view to forcing the solution into the aquifer formations offering resistance. As soon as the acid solution is poured, it should be agitated in the well for one to two hours, with the help of a surge plunger. The solution should then be bailed out. Bailing is continued until almost clear water is obtained.

In the second stage of treatment, the process is repeated using the same quantity of acid. Surging is continued for a longer period before bailing out the water. Generally, two treatments should be sufficient to achieve the desired results. During acid treatment, neighbouring wells within a 60 m radius should not be operated.

Adaptability. Hydrochloric acid treatment is best suited when the incrustation is due to calcium and magnesium carbonates. The treatment may not be successful in removing iron and manganese crusts. It attacks the steel well casing to some extent. However, damage can be minimised by using suitable inhibitors. Hydrochloric acid treatment is not suitable for agricultural strainers which consist of brass wire-mesh wrapped over a perforated galvanized iron pipe. In such a screen, treatment will result in rapid electrolytic corrosion of the screen.

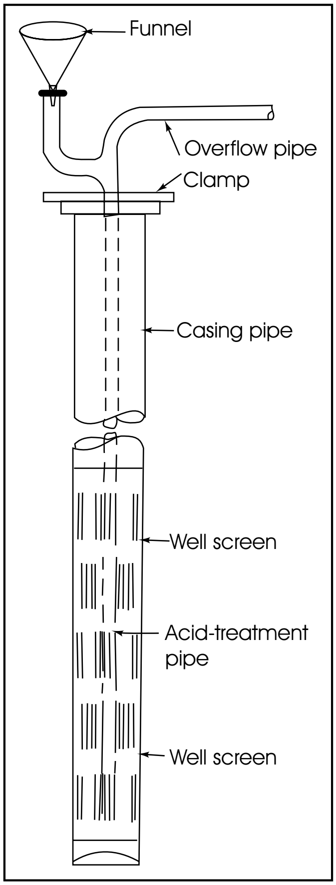


Fig. 7.16 Set-up for acid treatment of tube wells

Safety Measures. Hydrochloric acid is harmful to skin and can result in serious injury to eyes, if handled carelessly. Similarly, formation of gases, when the acid is poured into the well, can cause suffocation which could be fatal. Therefore, necessary care should be taken while treating the well. Good ventilation should be provided in the area around the pump house. All persons handling the acid should use rubber gloves and protective masks. A box of baking soda is kept handy, to neutralise the effect of acid if it falls on the body.

Sulphamic Acid Treatment

As discussed earlier, hydrochloric acid and sulphamic acid are used when calcium carbonate is the principal incrusting material. However, the former attacks mild steel well casings while the adverse effect of the latter is less. Hence, sulphamic acid is commonly used for treatment in case of wells having mild steel screens or casings with deposits of calcium and magnesium salts. Sulphamic acid (NH_2SO_3H), is commercially available in granular and pelletised forms (Fig. 7.17). It is available under different trade names like “aquamore”, “nu-well compound” etc. The safety of “aquamore” is increased by the addition of a corrosion inhibitor and a wetting agent. A colour indicator is also introduced in the pellet which would change the colour of the solution from violet to orange yellow, once the incrustation is completely dissolved. 'Aquamore' is soluble in water and the solution does not give any hazardous fumes. Sulphamic acid does not irritate the skin.

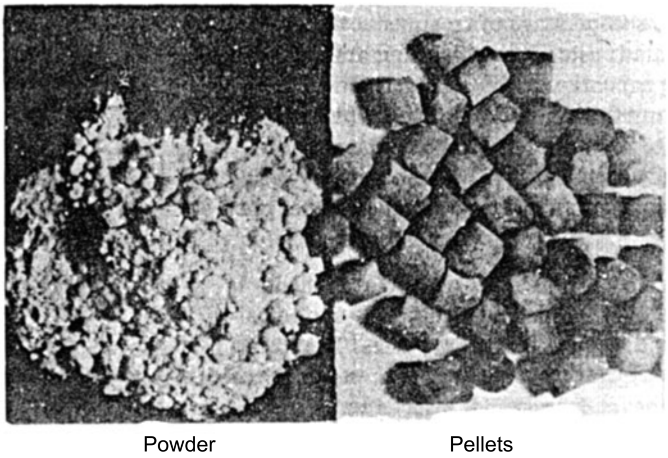


Fig. 7.17 Samples of sulphamic acid descalent in powder and pelletised forms
Courtesy: Gujarat Engineering Research Institute, Vadodara

Treatment Procedure. Sulphamic acid in granular form is poured into the well through a plastic or iron pipe. The material so poured is agitated to dissolve it in water. Sometimes it is poured into the well in a 20 per cent solution with water. In this case, first the solution is prepared by dissolving one bag of acid (powder or pellets) at a time in a 200-litre capacity drum. Arrangement is made for pouring the solution to the bottom end of the tube well. This is done by a 25 mm diameter PVC siphon tube, keeping one end of it in a funnel at the top of another 25 mm pipe already lowered into the bottom of the tube well, through the space between the pump and well casing. The end of the siphon is to be kept in the tank containing the sulphamic acid solution. The solution is then poured into the tube well through the pipe. The rate of feeding of the solution is controlled by a valve provided at the end of the delivery pipe so that the solution enters the tube well gradually in order to avoid faster chemical reaction at the initial stage. The feeding rate is regulated in such a way that the entire solution is added over a period of 2 or 3 hours. The solution is allowed to remain in the tube well for about 24 hours.

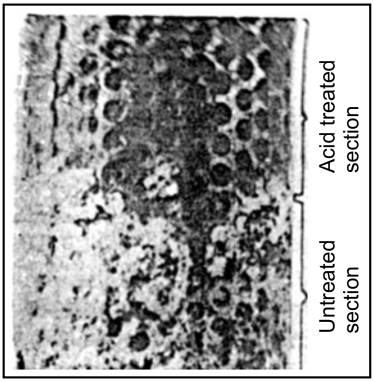


Fig. 7.18 Effect of sulphamic acid treatment on incrustation of well screen
Source: South Dakota State Univ. Extn. Ser. (Kenard, 1965)

When the acid is available in pelletised form, the pellets could be droped directly into the well in small quantities. Additional granular material is added to the well, as the reaction proceeds so as to keep the required strength of the solution. With surging, the reaction can be completed in 16 to 24 hours. After about 4 to 6 hours of adding the chemical, the well is developed by compressed air. This will loosen the incrusted chemical on the tube well screen and the surrounding aquifer. The tube well water is then pumped out. Pumping is continued intermittently for about 10 hours, till clean water is obtained.

The quantity of the sulphamic acid required depends on the quantity of water in the well. The usually recommended quantity of sulphamic acid (by weight) to be added in a tube well is about 7 to 10 per cent of the weight of water in the well. Thus, in a 20 cm diameter tube well with a water column of 100 m, the volume of water being 3.14 m^3, the total quantity of sulphamic acid required for a treatment is about 250 kg. It is often desirable to add a corrosion inhibitor and a wetting agent (low detergent soap) to improve the performance of the acid. The quantities of both these additives are about 10 per cent each of the weight of sulphamic acid. The corrosion inhibitor prevents corrosive action of the acid on the metal of the well pipe. The wetting agent improves the dispersing and cleaning action of the acid. Fluronic F-68 or Pluronic L-62 are commonly used as wetting agents. When the two additives are used with the acid, it is necessary to mix them in a bucket containing clean water, so as to form a heavy but pourable slurry, and add this slurry to the well through a tube.

The solubility of sulphamic acid decreases with decrease in temperature (Table 7.1).

TABLE 7.1 Solubility of Sulphamic Acid in Water

Temperature °C	**5**	**10**	**15**	**25**
Dry acid solubility in 100 litres of water, kg	17	18	20	23
Acid concentration of saturated solution, %	14	15	17	19

Source: Sharma and Chawla (1977)

Safety Precautions. Sulphamic acid in granular and pelletised forms is safe to use and can be handled with caution. However, when used as a concentrated solution, it should be very carefully handled. Water-proof gloves and goggles should be worn by those handling it. Hydrogen sulphide and carbon dioxide gases are produced in considerable volumes during the reaction. The former is produced when iron sulphate is present. Both these gases are heavier than air. Hence no person should be allowed to stand in a depression or a pit near the well during treatment.

In all acid treatments, the acid should be handled with care. Good ventilation should be provided when operating in a confined area, like a pump house. Adequate provision should be made for disposing the waste water which is pumped out during treatment. The waste water must be kept away from domestic wells, ponds or other water bodies used for human or cattle consumption. The waste, when diluted, will not adversely affect plants. Pumping the waste during acid treatment is a process of brisk surging, followed by slow pumping until the water becomes clear and free of odour and foam.

Aquifer Conditions which may not Respond to Acid Treatment

Acid treatment of water wells, though suitable under most conditions, may not result in any appreciable improvement under the following aquifer conditions:

1. Shallow, areally limited aquifers, subjected to recurring periods of over-draft.
2. Deeply burried narrow aquifers approaching over-development.
3. Aquifers of low permeability where operating heads are large.

Controlled pumping tests to determine well efficiencies and the hydraulic characteristics of aquifers are essential in determining the effectiveness of acid treatment or other development methods to increase the yield of water wells.

Necessary Conditions for Acid Treatment

The following are the major requirements for acid treatment of water wells:

1. The metal of the well screen must be such that it is not damaged by the acid.
2. The well screen must be constructed of a single metal in order to avoid electrolytic corrosion, as in the case of a bi-metallic alloy.
3. A fair knowledge of the kind of incrusting material is essential to determine the proper procedure in well treatment. Samples of incrustations taken from other wells in the same formation are useful indicators of the causes of incrustation. Water quality analysis is also useful to obtain information on the kind of incrusting material.
4. Adequate ventilation of well treatment site is necessary.
5. Wells located in the neighbourhood (within 30 m) of the well must be shut down during the process of treatment.

Glassy Phosphate Treatment

Glassy phosphate or polyphosphates are used for well treatment when iron oxide, manganese oxide, silt and clay are the materials causing incrustation. Sodium hexametaphosphate $(NaPO_3)_6$ is one of the most commonly used polyphosphates. They do not dissolve the incrusting material, and fuming or boiling does not take place. Phosphates have cleaning and dispersing properties which, when coupled with vigorous agitation, break the incrusting material. Thus, the incrustation gets dispersed and is easily pumped out. Calcium hydrochloride is also added to it in small quantities. It helps in chlorinating the well and killing the iron bacteria or similar organisms which may be present in well water.

Treatment Procedure. Glassy phosphate solution is prepared in a tank or drum. The amount of glassy phosphate to be added depends on the quantity of water in the well. Generally, 15 to 30 kg of glassy phosphate is used for every 1000 litres of water in the well. It should be dissolved in water by suspending it in a tank in a cloth net or gunny bag, and should not be simply dumped. A mixture of about 1.2 kg of calcium hypochloride per 1000 litres of water is desirable. It helps kill iron bacteria and other organisms. The solution so prepared is poured into the well. This is followed by vigorous surging, which will help the chemical loosen and disperse the deposits inside the pipe as well as outside. The dispersed material passes out through the screen openings. Surging can be done using a surge plunger, compressed air, or by horizontal jetting. If the pump installed in the wells is not removed, the same can be used for surging. Surging by pumping is not very effective but can be used for convenience. Surging with a pump is done by starting and stopping it as often as possible. Operation is continued for a period of about four hours. The pump is then left idle for about two hours. The process is repeated twice or thrice. When the chemical has been in the well for about 24 hours, surging is again repeated several times. The waste is then pumped out and the well flushed thoroughly. Even while the well is being flushed out, surging is done a few times at intervals, and pumping continued until fairly clean water is obtained, The entire procedure may be repeated two or three times, using a fresh charge of polyphosphates and calcium hypochloride. The chemical is quite safe to use and does not require any special safety precautions.

Chlorine Treatment

In case of wells incrusted with bacterial growth and slime deposits, chlorine treatment has been found most effective. Though acid may kill the bacteria, it is unable to remove the slime. Chlorine kills the bacteria as well as oxidises the organic slime, thus loosening it.

Calcium hypochlorite $Ca(OCl)_2$, is often used for chlorine treatment. It is available in powder form, containing about 70 per cent free chlorine. The quantity required is generally 20 to 25 kg for deep wells. Sodium hypochlorite (NaOCl) can also be used. Sometimes chlorine gas in water solution is also used but special equipment is required for its application.

Treatment Procedure. The desired amount of the chemical is put in the well directly, or in a water solution, to give the proper concentration of chlorine. When chlorine solution is used, it can be introduced into the well slowly through a plastic pipe of small diameter, over a period of about 12 hours in case of large wells. About 14 to 18 kg of chlorine will be required for this purpose. Small wells require less chlorine and the period of application can be decreased accordingly.

Chlorine is corrosive in the presence of water. It should, therefore, be handled carefully so that it does not harm the pump, well casing and screen. It is not necessary to remove the pump, but it should be ensured that the plastic pipe carrying concentrated chlorine solution is not discharging the liquid directly on any part of the pump, well casing or screen. As soon as the chlorine solution is introduced, a sufficient quantity of water (50 to 100 times the volume of water standing in the well) is added to the well from an outside source, with a view of forcing the chlorine solution into the water-bearing formation. The well is then surged, using any of the standard techniques already discussed. In case the pump has not been removed, the same can be used for surging, though not very effectively. Successful chlorine treatment of a well may require three or four successive operations. Chlorine is not inflammable and is not explosive. Hence, it is safe and does not require nay special precautions while using.

Alternate Treatments with Acid and Chlorine

Alternate acid and chlorine treatments are highly effective in removing incrustation in wells. The acid dissolves the carbonates while chlorine results in the effective removal of the slime deposited by iron bacteria. Both these treatments could be alternated, the acid treatment being performed first. The process of alternate treatment may be repeated two or three times. The procedure for each treatment is the same as already described.

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SHORT QUESTIONS

I State True (T) or False (F).

1. Steady decline in well yield results in tube well failure.
2. A sudden drop in the graph of well capacity versus time is an indication of failure of tube well due to incrustation.
3. Partial clogging of screen is indicated by increased drawdown in the well.
4. Gradual fall of gravel pack around the well indicates inadequate well development.
5. Over-pumping does not affect the specific capacity of the well.
6. Over-pumping may cause rupture of the well screen.
7. Delay in development of gravel pack tube wells may results in its failure.
8. The dewatered portion of the well screen accelerates the oxidation of salts in the water.
9. Bore-hole camera takes two-dimensional photographs.
10. Mechanical failures in tube wells occur due to corrosion and incrustation.
11. Impression block is a fishing tool.
12. Spuds are used to fish out lost drill pipes.
13. Corrosion and incrustation can occur at the same time.
14. Incrustation increases with increase in *p*H of ground water.

15. Incrustation causes enlargement of screen slot opening.
16. Dissolved oxygen in ground water increases the rate of corrosion.
17. Chemical corrosion is an electrochemical phenomenon.
18. Presence of chlorides and sulphates of ferrous metal increases the corrosion rate.
19. Copper has the least resistance against corrosion.
20. Galvanic corrosion results due to presence of two metals in a conducting solution.
21. Rigid PVC pipes are susceptible to corrosion.
22. Corrosion rate decreases in wells as the hydrogen sulphide concentration in ground water increases.
23. Decrease in the rate of pumping has been found to reduce corrosion.
24. Cathodic protection of tube well is applied against incrustation.
25. Soft incrustation is the result of presence of carbonates in water.
26. Presence of water-soluble sulphates causes hard incrustation.
27. Hard incrustation is easy to remove.
28. Presence of iron bacteria in ground water has been found to increase incrustation.
29. Mechanical incrustation may take place due to deposits of silt and clay in well screen.
30. Carbonate-type incrustation is removed by hydrochloric acid treatment.
31. Incrustation of manganese and iron oxides cannot be removed by hydrochloric acid treatment.
32. The sulphamic acid treatment is commonly used in case of wells having mild steel screens.
33. The quantity of sulphamic acid required for treating incrustation depends on the quantity of water in the well.
34. Presence of wetting agent in acid treatment prevents corrosive action of acid on the metal of the well pipe.
35. Presence of inhibitor improves the dispersing and cleaning action of acid.
36. Polyphosphates are used for well treatment when iron and manganese oxides are the material causing incrustation.
37. Chlorine treatment has been found most effective in case of wells incrustated with bacterial growth and saline deposits.
38. Alternate acid and chlorine treatment are not effective in removing incrustation in wells.
39. In alternate acid and chlorine treatment, the acid treatment should be preferred first.
40. Addition of calcium hydrochloride helps in chlorinating the wells and killing the iron bacteria.

Ans. True: 1, 3, 4, 6, 7, 8, 13, 14, 16, 17, 18, 20, 23, 25, 26, 28, 29, 30, 32, 33, 36, 37, 39, 40.

II Select the correct answer.

1. Hydrochloric acid treatment is best suited when incrustation is due to
   (a) ferrous bicarbonate (b) calcium carbonate
   (c) iron bacteria (d) mechanical
2. The usually recommended quantity of sulphamic acid (by weight) to be added in a tube well is about
   (a) < 5 per cent of the weight of water in the well
   (b) 5 to 10 per cent of the weight of water in the well
   (c) 12 to 15 per cent of the weight of water in the well
   (d) > 15 per cent of the weight of water in the well

3. The addition of wetting agent in sulphamic acid treatment
   (a) improves dispensing action (b) prevents corrosion
   (c) kills bacterial growth (d) removes slime
4. Incrustation in the form of slime is produced by
   (a) calcium carbonate (b) deposits of silt and clay
   (c) magnesium carbonate (d) iron bacteria
5. The ground water is expected to be incrustative when
   (a) *p*H value is less than 7.5 (b) carbonate content exceeds 300 ppm
   (c) iron content is less than 2 ppm (d) TDS exceeds 1000 ppm
6. Water is considered corrosive when
   (a) dissolved carbon dioxide is less than 50 ppm
   (b) electrical conductivity is greater than 1.5 dS/m
   (c) *p*H is more than 7.0
   (d) dissolved oxygen is less than 2 ppm
7. Incrustation results in
   (a) clogging of well screen (b) enlarging of well screen
   (c) corrosion of pump component (d) reduction in strength of the screen
8. Under corrosive conditions, well screens should be designed with
   (a) small open area (b) normal open area
   (c) large open area (d) gravel pack
9. The yield of low discharge from a well is due to
   (a) over-pumping (b) inadequate well development
   (c) corrosion (d) pitting
10. A sudden drop in the well capacity is an indication of failure of tube well due to
   (a) corrosion (b) incrustation
   (c) over-pumping (d) poor strate

Ans: 1 (b) 2 (b) 3 (a) 4 (d) 5 (b) 6 (b) 7 (a) 8 (c)
9 (b) 10 (a)

8

Man and Animal Powered Water Lifts and Positive Displacement Pumps

Devices for irrigation water lifting range from age old indigenous water lifts to highly efficient pumps. The earliest water lifts were simple man-powered devices, many of which are still being used with modifications in various forms. When ways of obtaining mechanical advantage became known, man began to apply the principles of simple machines, like the lever, pulley, screw and inclined plane, in water lifting. This was followed by the development of positive-displacement piston pumps operated manually or by windmills. The advent of mechanical power and modern machinery revolutionised the technology of water lifts to meet almost any requirement. The selection of a suitable water lifting device for a particular situation depends on the characteristics of the source of water and the lifting device, the amount of water to be lifted, the depth to water table, the type and amount of power available and the economic status of the farmer.

Man and animal power are the major energy sources in small scale irrigation pumping and water supply in many regions of developing countries. From a purely economic standpoint, however, the cost of raising water with man or animal power is substantially higher than that with mechanically powered pumps. Studies have revealed that the cost of raising a unit quantity of water (say 1 m^3 to 1 m height) is the lowest in case of pumps operated by electric motors. The relative cost for engine-operated pumps is about 15 to 25 per cent more than that of electric motor-driven pumps. The cost of lifting water by animal power is about 10 to 20 times more than with electric motors. Manually operated water lifts are the costliest, being 3 to 4 times more than animal-operated devices. In spite of the economic disadvantage, man and animal power continue to remain the major energy sources in domestic water supply and small scale irrigation in developing countries, where alternative demand for these sources of power are not adequately developed. Small land holdings, lack of adequate mechanical skill amongst farmers in operating pumping sets and their low economic status often necessitate the use of man and animal power in water lifting in developing countries.

Though the terms water lift and pump are often used synonymously, the former, as used in this text, refers to water lifting devices which do not incorporate the use of pistons and plungers, impellers, gears or similar other mechanisms to pump water.

Principles of Lifting and Moving Water

Water may be lifted by any one of the following mechanical principles:

1. *Direct lift*. It involves physically lifting water in a container.
2. *Atmospheric pressure*. Water is lifted by atmospheric pressure by creating a vacuum in a chamber which sucks water up to a maximum pressure head of one atmospheric pressure (approx. 10 m).
3. *Positive displacement*. It involves pushing or displacement of water from a lower to a higher level (water being effectively incompressible).
4. *Creating a velocity head*. The momentum created by propelling or rotating water at high speed is utilized to create a flow or create a pressure.
5. *Using the buoyancy of a gas*. Air (or other gas) bubbled through water will cause movement of columns of water due to difference in specific gravity.
6. *Using the impulse (water hammer) effect*. Water hammer effect results in a sudden sharp rise in water pressure to carry a small part of the supply upto a considerably higher level.

Water lifting devices, including pumps embody one or more of the above principles to lift water from its source to the desired level. The classification of water lifts and pumps based on the principles of operation is shown in the accompanying chart.

Several types of indigenous water lifts are in use in small scale irrigation. All of them, with slight modification, are to be found in Asia, Africa and South America. They may be manually operated or animal driven. Table 8.1 presents the performance characteristics and adaptability of some common types of indigenous water lifts.

8.1 MANUALLY OPERATED WATER LIFTS

Human power is frequently employed in water lifting for small scale irrigation and rural water supply in almost all developing countries. Though from an economic analysis it is the most expensive form of power, the socio-economic conditions in many regions of the world demand the continued use of this source of power in water lifting and other farm work.

Water Lifts and Pumps

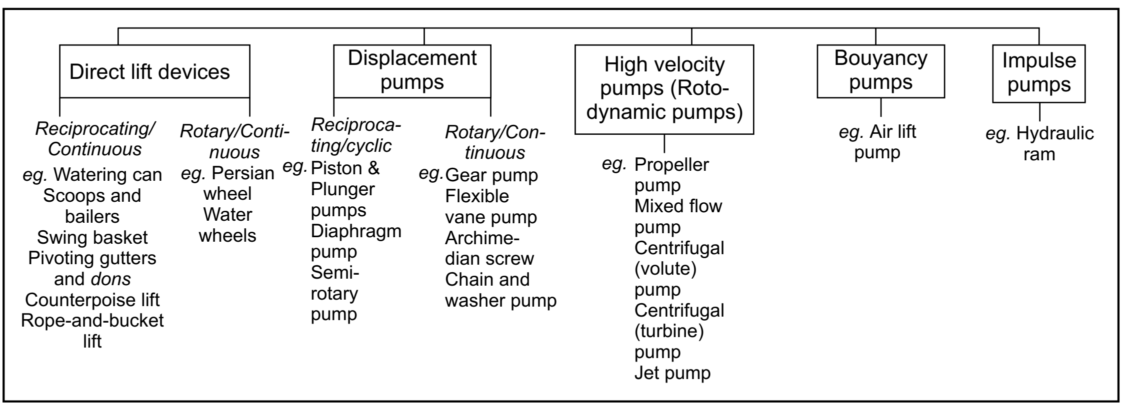


TABLE 8.1 Performance and Adaptability of Commonly used Indigenous Water Lifts

Name of device	**Kind of power**	**Lift m**	**Average discharge *l/h***	**Remarks**
Swing basket	Two men	0.5 – 1.2	7,000 – 10,000	Used in rice growing belts in developing Countries
Oscillating trough (*Don*)	Single man	0.5 – 1	9,000 – 14,000	Commonly used in the eastern region of India, Bangladesh
Archemedian screw	One or two men	0.5 – 1.2	14,000 – 19,000	Commonly used in the Godavari delta of Andhra Pradesh (India) and in Lower Egypt
Water wheel (animal operated)	One pair of bullocks (or single camel/ buffalo) and one man	0.8 – 1.2	40,000 – 60,000	Commonly used in the canal irrigated areas of north India, to lift water from water courses which run below field level
Persian wheel	One pair of bullocks or buffaloes, or single camel, and one man	5 – 10	14,000 – 18,000	Traditional water lift in northern India, Pakistan, Iran, Iraq and Egypt
Animal-operated Chain pump	One pair of bullocks and one man	3 – 6	15,000 – 20,000	Used in some parts of Uttar Pradesh
Self-emptying type Rope-and-bucket lift	One pair of bullocks and one man	4 – 6	10,000 – 15,000	Commonly used in southern India, the Deccan region and parts of Rajasthan
Circular two-bucket lift	Single bullock and one man	4 – 5	12,000 – 14,000	Used in some parts of Tamil Nadu
Counterpoise-bucket lift	Single man	1.2 – 4	8,000 – 11,000	Commonly used in southern India, Bihar and the Deccan region. Extensively used in Egypt, Sudan and other developing countries
Leather bucket lift (*mhote or charas*)	Two pairs of bullocks and three men	10 – 30	6,000 – 10,000	Commonly used in Rajasthan, Maharashtra and other areas with deep water table

Human Beings as Power Source

The human work capability is about 250 watt-hrs per day. In other words, it takes about 4 days of hard labour to deliver 1 kilowatt-hr of energy. Human beings (and animals) derive their power from the calorific content of the food they eat. Human beings have an overall efficiency of 7 to 11 per cent for converting food energy to mechanical energy. However, the efficiency of the muscles for short effort can be as high as 20 to 30 per cent. Thus, muscle power can handle quite large overloads for short periods, but the power capability diminishes gradually. The power capability of a human being depends on the build, age, state of health and weight. Table 8.2 presents the results of tests on human power capability measured by the Blair Research Institute in Zimbabwe, Africa.

TABLE 8.2 Human Power Capabilities

	Human power by duration of efforts, watts					
Age (years)	**5 min**	**10 min**	**15 min**	**30 min**	**60 min**	**180 min**
20	220	210	200	180	160	90
35	210	200	180	160	135	75
60	180	160	150	130	110	60

Based on Morgan's letter in Appropriate Technology Jl., London, Vol. 9 No. 1, 1983. Quoted from Fraenkel (1986).

The actual useful output from a person depends greatly on the way the water lifting device works or the 'ergonomics' of the design of the water lift. The most powerful muscles of a human being are the leg and back muscles. The arm muscles are relatively week. Hence, conventional hand pumps are less effective in manual operation than pedal operated water lifts. For the efficient operation of water lifts the operator needs to be comfortable in his working position and should not be constrained into some difficult position. The operator should also be well balanced and be on a relaxed posture for efficient functioning. He/she should work at a comfortable speed of operation. In many cases the utilization of the leg muscles will allow the operator to throw his/her weight behind the effort in order to add to the pedal pressure.

Where pumps are used for water supply, the efficiency of the operator is not a major concern as the water lift is operated only for a few minutes at a time to fill a few small containers. Hence, hand-operated devices are usually preferred as they are lighter, smaller and easy to install. However, such pumps will not be efficient for use in irrigation which require larger quantities of water and a continuous supply spread over several hours. Hence, the criteria for defining a good manually operated irrigation pump is distinctly different than those for a water supply pump.

Based on the range in the height of lifts, human-powered water lifts are grouped under devices for low, medium and high heads.

8.1.1 Low-Head Water Lifts

The scoop, swing basket, oscillating trough (*don*), Archimedian screw, water ladder and water wheel are the commonly used manually-operated water lifts, when the depth to the water surface does not exceed 1.2 m.

Scoop, swing basket and oscillating troughs represent devices, for speeding up the process of filling, lifting and emptying a bucket. However, they are inefficient, as compared to other manually operated water lifting devices, since water is lifted to a higher level than the ground surface and then allowed to fall.

Scoop

The scoop is the oldest and the simplest of the water lifting devices used by man. It consists of a wooden trough provided with a handle. It is used as a simple hand tool or as a ladle suspended by a rope from a wooden tripod (Fig. 8.1). It is usually operated by a single man, to lift water from streams and pools, to irrigate paddy fields. It is also used for dewatering paddy fields. When used with a tripod, the operation of the scoop includes dipping, swinging and tipping, with a minimum of lifting. The height to which water can be lifted is limited to about 1 m. The discharge varies from 5000 to 7000 litres per hour.

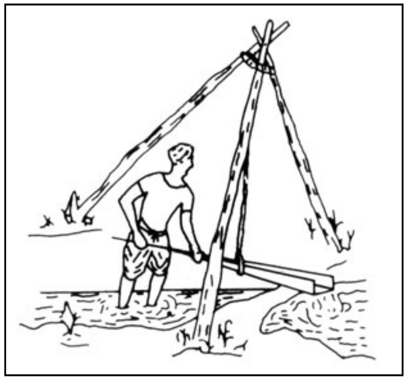


Fig. 8.1 The scoop, with rope and wooden tripod is used to lift water from a shallow stream

Swing Basket

The most ancient water lift, after the scoop, is the swing basket, sometimes called bucket scoop. It consists of a basket or shovel-like scoop to which four ropes are attached (Fig. 8.2). Two persons stand facing each other on either side of a water source, holding ropes connected to a triangular shaped basket made of woven cane, plain sheet steel, or the flattened tin of a used container. In a rhythmic motion the basket is lowered into the water source, then simultaneously pulling on the ropes, the basket swings upward. At the moment of discharge a sharp tug on the rope connected to the bottom of the basket inverts it and discharges the water. Certain types of swing baskets can discharge into the field channel. Four persons are required to operate a basket throughout the day, working in two-hour shifts.

Fig. 8.2 Two swing baskets in simultaneous operation by two pairs of operators. Note the farmer couple on the stream bank. The operators on the other side are not visible in the picture
Photo: Ministry of Information and Broadcasting, Govt. of India

Oscillating Trough or Gutter (Don)

The oscillating trough or *don* is a manually operated boat-shaped trough or gutter made of wooden planks or hollowed local trees. It is closed at one end and open at the other. A flap valve could be provided at the bottom, near the closed end, to facilitate filling of water. The open end is hinged at the discharge end at the bank of the ditch. If closed, it is provided with a valve at the bottom. The trough is usually made of half the stem of a hollowed tree, or of sheet metal. The closed end of the trough is tied with a rope to a long wooden pole which is pivoted as a lever on a post (Figs. 8.3 and 8.4). A weight, a larger stone or a dried mud ball, is fixed to the shorter end of the lever. The trough oscillates on a fixed center so that one end is alternatively dipped into the water and raised above the level of the delivery point. The weight of water is equalized by the counterbalance weight on the short end of the pole. The counterpoise structure is usually located on the opposite bank. The lever and the counterpoise are adjusted to provide a greater moment (i.e. weight times the lever arm) than the full trough. The operator, who stands on a scaffolding made of bamboo or wooden plank over the water, depresses the end of trough into the stream with his feet (Fig. 8.3). He then steps on to the scaffolding and lifts the filled trough slightly with his hands and slopes it towards the point of delivery, thus enabling the water to run out into the field channel.

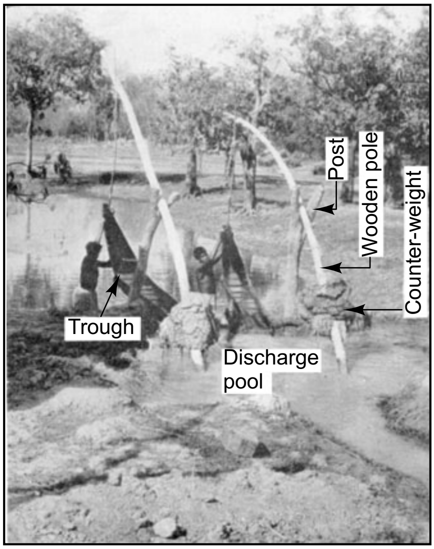


Fig. 8.3 *Don* used to lift water from a shallow stream to irrigate a rice field. *Don* is a commonly used water lift in rice irrigation in West Bengal,Orissa and parts of Bihar and in Bangladesh

Several modifications and improved designs are available in oscillating-trough-type water lifting devices. In the seesaw trough (Fig. 8.5), the operator shifts his weight back and forth. An outboard flap valve facilitates filling. Another design provides for the operator to walk back and forth, on a notched lever, to provide a movable counterweight (Fig. 8.6). The trough is attached at both ends to the lever. The design results in a greater rate of discharge than the conventional designs shown in Figs. 8.3 and 8.4. Two comparatively recent designs of the oscillating trough are shown in Fig. 8.7. Figure 8.7a illustrates the use of a pair of floats (sealed air containers, e.g. a petrol can) to lift the trough by buoyancy instead of counterweight. The operator merely steps on the outboard end of the trough to fill it and steps off to allow buoyancy to lift it.

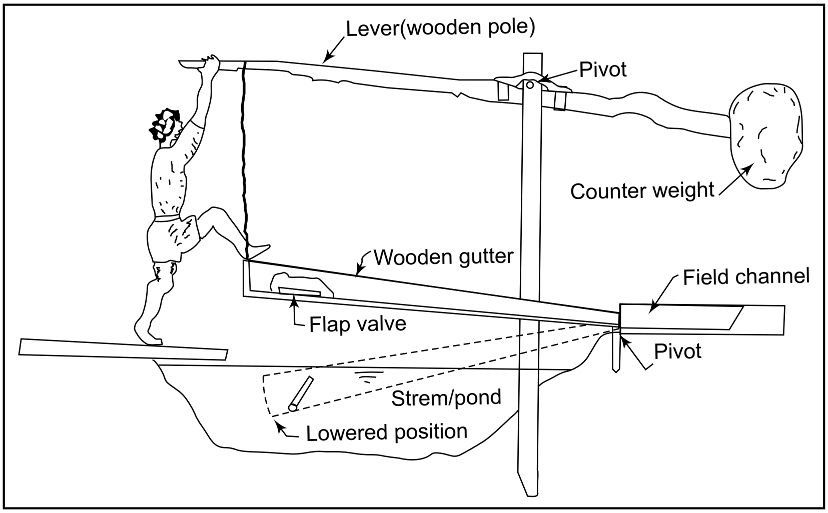


Fig. 8.4 Schematic sketch illustrating the operation of a *don*, provided with flap valve

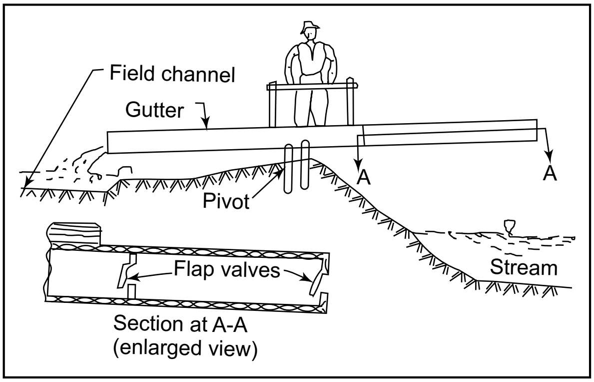


Fig. 8.5 Schematic sketch of a see-saw trough
Adapted from: Wood *et al*. (1977)

Figure 8.7b illustrates a double-acting foot-operated trough. It comprises a pair of troughs connected by a rope which passes over a pulley. The operator stands with one foot on each trough and alternately shifts his weight from one pan to the other. By means of a flapped opening in the outboard end of each pan, it fills and is then raised and drained out through the shore-hinged end. The device, however, is limited to lifting water to heights ranging from 30 to 50 cm only, but is quite efficient and easy to operate. The discharge is about 25000 *l*/h when the lift is 30 cm.

Pedal-Operated Water Snail

The basic screw or auger for lifting is merely an inclined surface rotating around a central axis. When used as a water lift, it pushes water up an incline. One of the earliest designs of a water lifting screw is the water snail, utilizing a flexible tube wrapped around and secured to an inclined axle (Fig. 8.8).

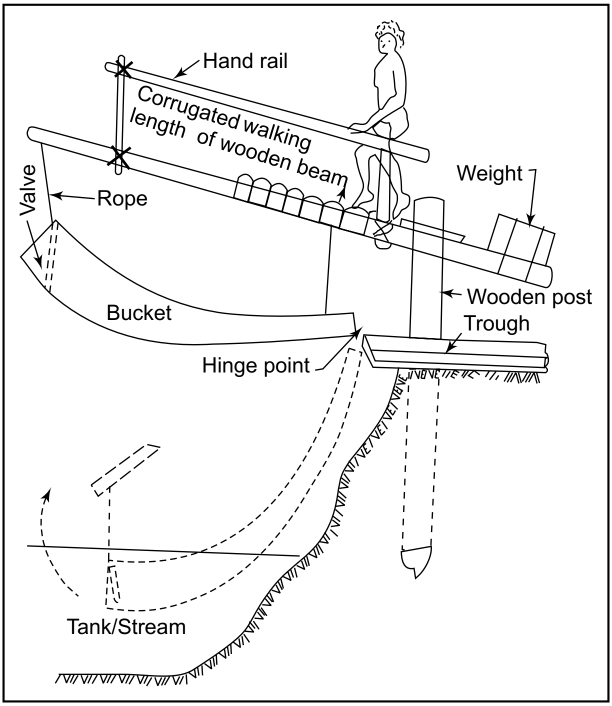
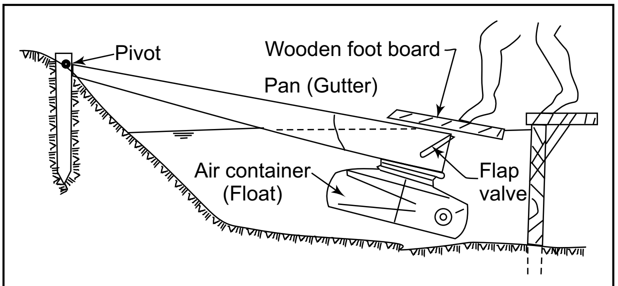


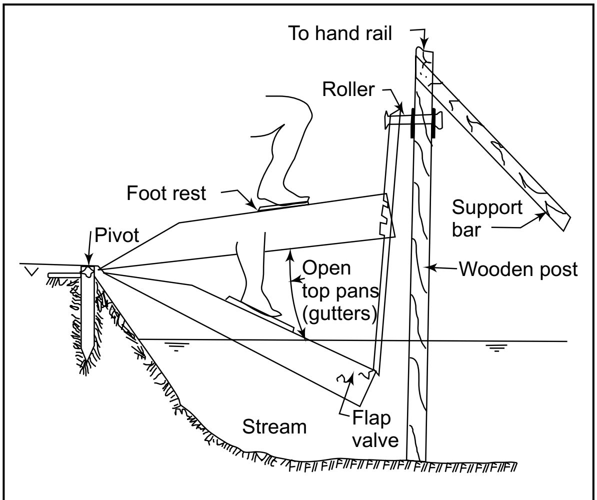
Fig. 8.6 A swing bucket (*don dall*) with counterpoise arrangement and using the principle of shifting weight by the operator who walks on the beam

Archimedian Screw

The Archimedian screw, also called Egyptian screw, is probably the most efficient amongst the manually operated water lifts. It is said to have been invented by Archimedes, in about 200 BC, when King Heiron II of Syracuse (Sicily) asked him to invent a method to drain the holds of his ships. The Archimedian screw is popular in the Godavari delta of India and in Egypt to lift water from shallow sources, where the lift is within 25 to 120 cm. It is a helicoid fitted within a cylinder (A helicoid may be defined as the surface generated when a line perpendicular to an axis rotates about it). The device consists of a drum with an interior partition in the form of an auger-like spiral, rotated by means of a handle fixed to a central shaft (Fig. 8.9). The screw may be of welded steel or plastic. It may also be made of a series of short boards or battens, about 2.5 × 5 cm in cross-section (Fig. 8.10b). The boards are fitted on to a steel shaft about 2.5 sq. cm. Each successive batten is skewed so that its edge overlaps the preceding one by about 1 cm at the outer ends. The edges of the battens are shaped to provide a smooth surface. The screw is encased in a sheet-metal or wooden cylinder called a drum. Wooden cylinders are made of boards of 1.25 to 5 cm width and about 1 cm thick. Iron bands, spaced about 30 cm apart, hold the boards of the cylinder in place. The diameter of the cylinder ranges from 40 to 60 cm and its length from 1.5 to 2.7 m. The shaft projects from both ends and is supported at the base and near the upper end, on posts. The screw is placed at an angle, with its lower end in water. When the handle is turned, water moves up through the screw and discharges at the upper end of the cylinder (Fig. 8.10(a)).



(a) *Don* equipped with air float



(b) Double-acting pedal operated *don*

Fig. 8.7 Views of improved versions of *don*
Adapted from: Wood *et al.* (1977)

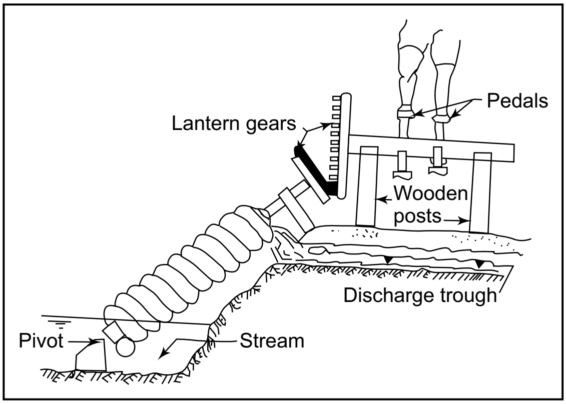


Fig. 8.8 Pedal-operated water snail
Adapted from: Wood *et al*. (1977)

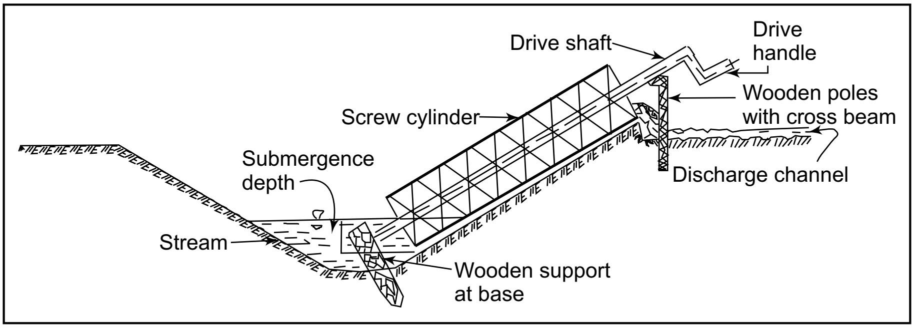


Fig. 8.9 Details of installation of an Archimedian screw to lift water from a stream

Generally, the Archimedian screw is operated by one man who can work a maximum of four hours at a stretch (Fig. 8.10a). Sometimes, the screw is operated by two men who either face each other while turning the screw or work in shifts.

Fig. 8.10 (a) An Archemedian screw (Egyptian screw) being used to lift water from a field channel (minor canal) for irrigation
Courtesy: FAO, Rome

The performance of an Archimedian screw is influenced by the angle of inclination of the screw β, the speed of rotation and the depth of submergence of its lower end. The angle of inclination of the screw (Fig. 8.11) ranges between 30º and 35º. Studies by Srivastava and Michael (1965) indicated that the discharge and efficiency of the screw were maximum when the angle of inclination was 31º. There was a sharp decrease in efficiency as the angle was increased. The efficiency of the screw was maximum when its speed of rotation was 40 rpm. Higher speeds reduced the discharge. The screw was observed to perform most efficiently when its bottom was submerged a little more than half (approximately 1 cm above the center of the shaft). Full submergence reduced the efficiency by about 20 per cent. The submergence of the screw below the water is usually expressed as the difference between the elevations of the fill point and the touch point (Fig. 8.11). The depth of submergence is determined as follows:

Fill point elevation – Touch point elevation = 0.751 D cos β in which,

D = Diameter of the screw

Large size power-driven screw pumps are used in the Netherlands in drainage pumping of sewage water and industrial waste. The size of these pumps vary from 40 to 300 cm in diameter, with discharge capacities ranging from 25 to 3000 1/s.

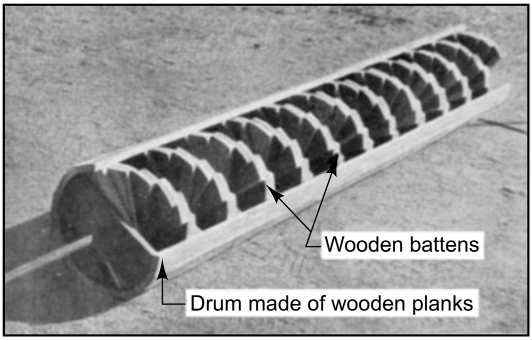


Fig. 8.10 (b) An exposed view of an Archimedian screw made of wooden battens

Paddle Wheel

The paddle wheel (Fig. 8.12) is a simple pedal-operated water lifting device used for watering and dewatering of paddy fields. It is a traditional device which was in extensive use in South-East Asian countries and the Far East till the introduction of pumps. In India, it has been in use in the paddy growing areas of Kerala where it is known as a *chakram.* The device in its simple form, consists of wooden blades mounted radially on a horizontal shaft (Fig. 8.13). The ends of the shaft are supported on a wooden frame-work. The device is more efficient than the scoop and is easy to operate. The wheel is operated by pedalling the treadles, with the arms and upper part of the body of the operator supported on a wooden or bamboo frame. The operation is less tiring than the arm and back motion involved in using a scoop or swing basket.

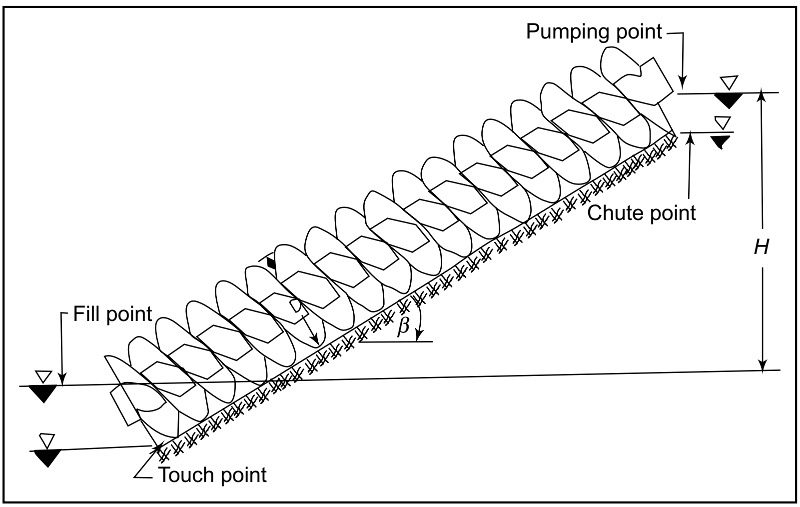


Fig. 8.11 Definition sketch illustrating the basic factors influencing the operation of Archimedian screw made of sheet metal

Fig. 8.12 A paddle wheel in operation to lift water from a paddy field into a channel in the Kuttanad area of Kerala!

An improvement over the traditional paddle wheel is the provision of a close-fitting concave trough at the front lower quarter of the wheel. This reduces the spilling of water from the edges of the paddles and increases both the lift and discharge of the device.

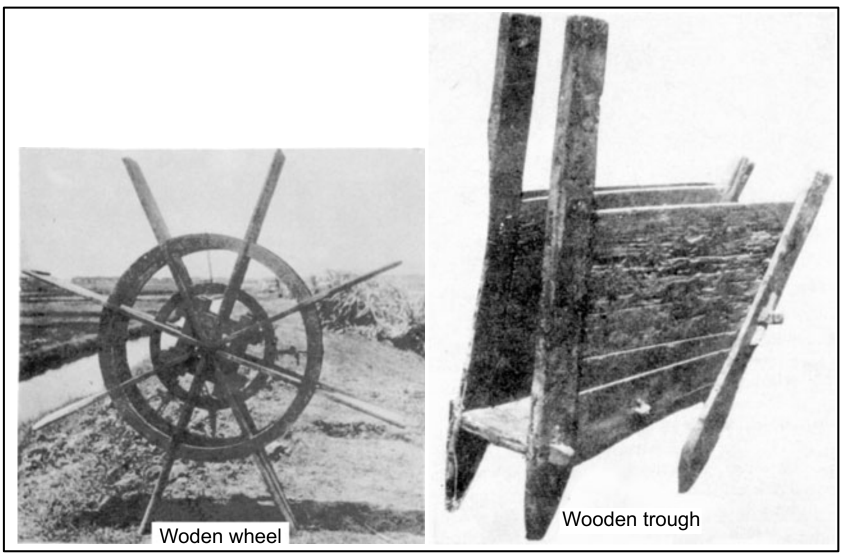


Fig. 8.13 Close views of the wooden wheel and trough of the manually operated paddle wheel shown in Fig. 8.12

The number of blades in the wheel varies from 8 to 24, depending on its diameter. The diameter of the wheel depends on the lift involved. The smaller sizes are used where the water level is within 0.6 m from the ground. Large sized wheels are used for lifts as high as 1.2 m. The discharge varies from 10,000 to 14,000 1/h.

8.1.2 Medium-Head Water Lifts

Medium head water lifts are suitable when the height of lift is within the range of 1.2 to 5 m. Manually operated medium head water lifts suitable for small scale irrigation includes the counterpoise bucket lift and the manually operated chain pump or bucket pump (Persian wheel).

Counterpoise Bucket Lift

Counterpoise bucket lifts are used in many regions of developing countries. The device consists essentially of a long wooden pole which is pivoted as a lever on a post (Fig. 8.14). A weight, usually a large stone, a ball of dried mud, or a basket of stones, is fixed or hinged to the shorter end of the pole. This weight serves as a counterpoise to a bucket suspended by a rope or a rod attached to the long arm of the lever. The bucket may be made of sheet metal or leather or may consist of a large earthenware pot. To operate the lift, a man pulls down the rope or rod, using his body weight and strength, until the bucket is immersed in the water and filled. The bucket is drawn up by the counter weight. As it reaches ground level, it is tipped into a trough. Generally, the working range of a counterpoise lift is between 1 and 3 m. For higher lifts, two or more of the devices may be used in series.

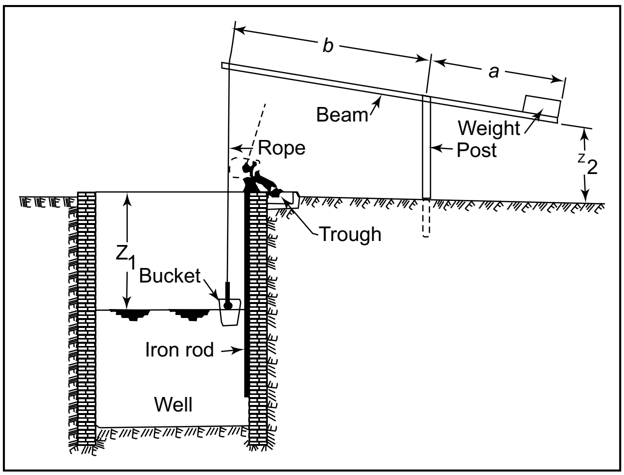


Fig. 8.14 Schematic sketch illustrating the principle of working of a counterpoise bucket lift with self-emptying mechanism. (Note the iron rod fixed to the well wall and the steel-rod hook fixed to the bucket which slides on the rod)

The counterpoise is adjusted to balance the weight of the full bucket. The proper weight of the counterpoise can be computed as follows:

$$W_1 = \text{weight of bucket, kg}$$

$$W_2 = \text{weight of water in bucket, kg}$$

W_3 = weight of counterpoise, kg

Z_1 = lift or motion of load, m

Z_2 = motion of effort, m

a and *b* are the lengths of the weight arm and force arm of the oscillating lever (Fig. 8.14).

$$\text{Velocity ratio} = \frac{\text{Motion of effort}}{\text{Motion of load}}$$

$$= \frac{Z_2}{Z_1} = \frac{a}{b}$$

Now $$(W_1 + W_2)\, b = W_3 a$$

or $$\frac{W_1 + W_2}{W_3} = \frac{a}{b} = \frac{Z_2}{Z_1}$$

$\therefore$ $$W_3 = (W_1 + W_2)\frac{b}{a} \quad (8.1)$$

The *picottah* (Fig. 8.15), commonly used in South India, is an adaptation of the conventional counterpoise lift. This is built with a massive wooden framework to enable the operator to walk on the pivoted pole. In operating the device, one or two men walk back and forth on top of the pole.

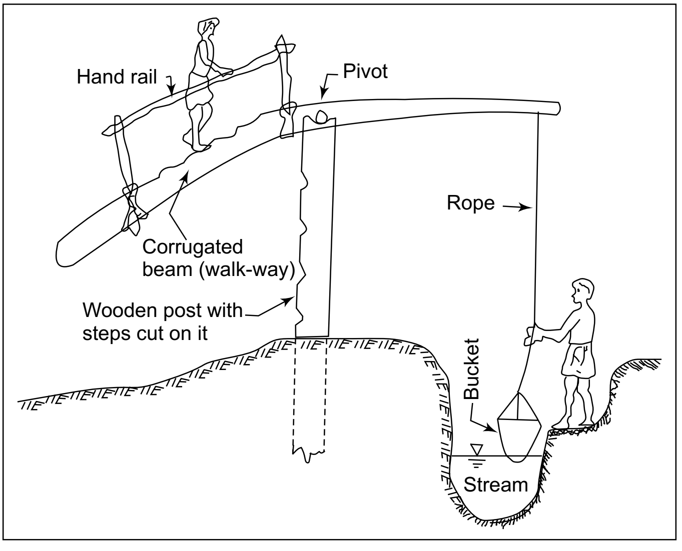


Fig. 8.15 A two-man operated counterpoise bucket lift, using the principle of shifting weight by the operator who walks on the beam

The pole is notched along its upper surface to provide a foothold. A hand rail is provided on the pole, or as a separate frame-work. As the men walk, their body weights are shifted which causes the bucket to be lowered and raised. A separate person is required to empty the bucket. The device, being larger, is capable of lifting water from depths between 5 and 8 m. The output, however, is low and its use is confined to irrigating vegetable plots.

Manually Operated Chain Pump

The chain pump is a traditional water lifting device and its origin dates back to the early part of the first century A.D. It consists of a series of linked discs or plugs which are pulled through a pipe. They are usually manually operated or animal driven. It is also suitable for operation with a windmill. A major advantage of the chain pump is that it requires a steady rotary power input which suits the use of a crank drive with a flywheel which is mechanically efficient and comfortable in applying the muscle power. It can also be used over a wide range of operating heads. For low heads, loose fitting washers are adequate. At higher heads, tight fitting plugs rather than washers may be necessary to minimize back leakage. Many materials have been tried to make washers. But rubber or leather washers supported by smaller diameter metal discs are the most suitable.

A manually operated chain pump consists of an endless chain, provided with discs or washers at intervals working in a vertical pipe (Figs. 8.16). It can be operated by human or animal power. It is an efficient device for lifting water from shallow open wells of small diameter and works best when the

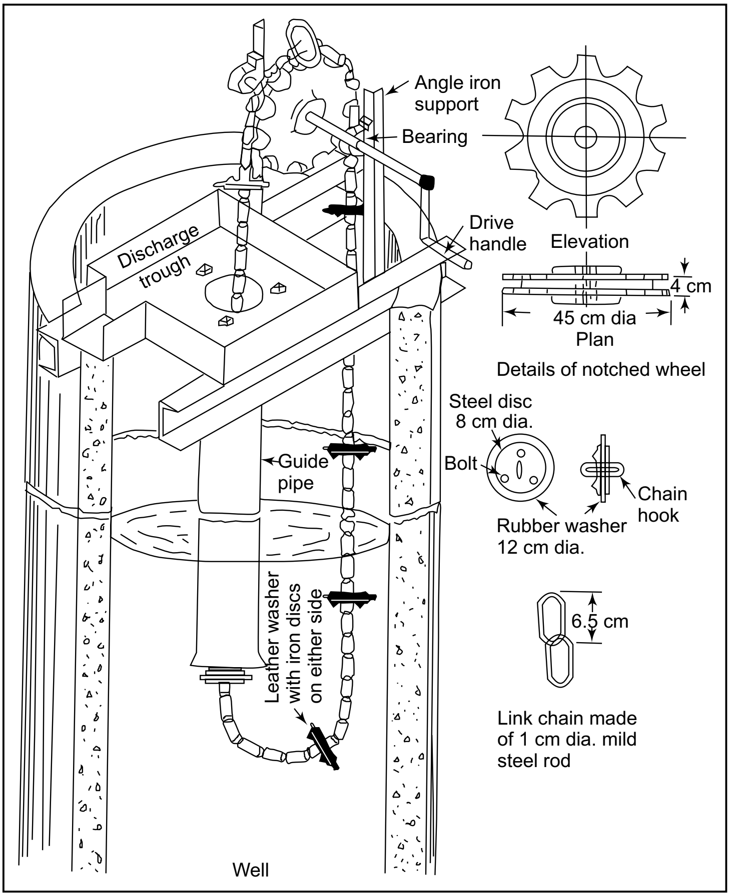


Fig. 8.16 Isometric view of a chain pump installed in a small diameter open well. (The well is shown in section)

lift is less than 5 m. The washers are spaced about 25 cm apart. In some recent designs, leather washers, strengthened by iron washers, are being used to make the discs. The chain passes over a notched wheel, called the winch shaft, mounted on a suitable platform fixed on top of the well. A crank handle of wood or metal is bolted or welded to the winch shaft. On one side of the chain is a pipe of about 10 cm diameter, with a flared opening at the bottom and connected to a trough at the top. The bottom of the pipe is submerged about five chain links (60 to 90 cm) below the surface of the water. The disc washers have the same diameter as the inside of the pipe. When the wheel is turned, each disc brings up a volume of water. Both the capacity of the chain pump as well as the power requirement in operating it are proportional to the square of the diameter of the pipe.

8.1.3 Deep Well Water Lifts

Manual water lifting from deep wells is limited to domestic water supply. The discharge of these lifts is too small to be used even for small-scale irrigation. The age-old rope-and-bucket lift, working on cast iron or wooden pulleys, still remains the only manually operated device suitable for deep wells (Fig. 8.17). The practice of each family having its own rope and bucket to draw water from a community well is frequently a health hazard. Sanitary protection of wells requires the use of a common water lift which is kept protected from direct human contact. The details of a sanitary rope-and-bucket arrangement is shown in Fig. 8.18. The rope is fixed to a drum (windlass) on which it winds when rotated from outside by a handle. The rope passes through a guide which prevents swinging of the bucket while in operation. As the bucket reaches the trough, it is automatically tipped, the water discharged into the trough, and collected in buckets.

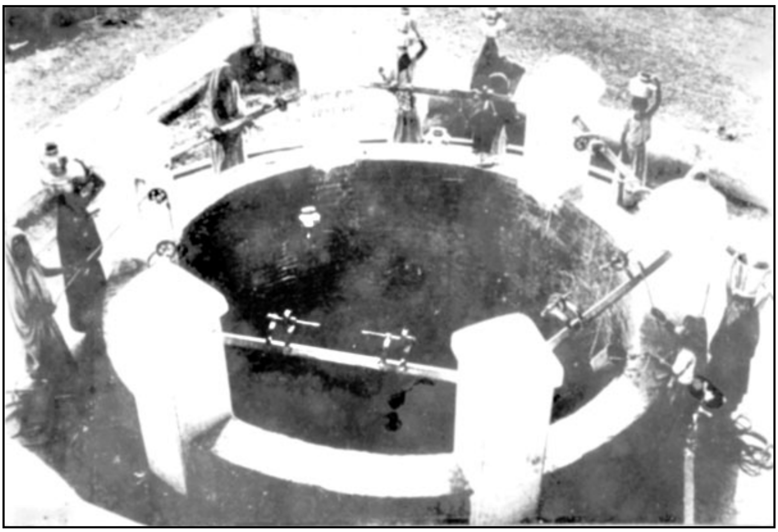


Fig. 8.17 A community open well in Limgaon village in Hoshangabad district, Madhya Pradesh. Note the people drawing water with their own buckets and ropes, thus contributing to the pollution of the well water
Photo: Ministry of Information & Broadcasting, Govt. of India

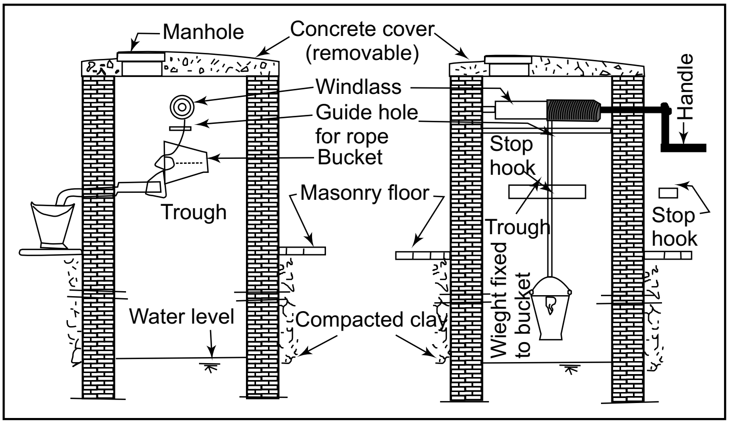


Fig. 8.18 Views of sanitary rope-and-bucket arrangement in an open well

8.2 ANIMAL POWERED WATER LIFTS

In countries where animal power is utilized for agricultural operations, animal-driven water lifting devices are often used. Use of an animal in water lifting provides the equivalent power of 5 to 10 men, generally at a fraction of the cost. Animals can lift more water in a shorter time which makes irrigation operation more efficient. Further, most of the men who could have been engaged in operating the lift are released to attend to the water distribution system effectively and for undertaking other cultural practices on the farm, thus increasing farming efficiency.

There is considerable scope to increase the efficiency of animals in operating water lifts and also increasing the efficiency of these devices. The efficiency of the animal is increased by matching the power of the animal to that required for the particular water lift and by adopting improved animal harnesses, and better hitching techniques.

Indigenous water lifts, described in this chapter, usually employ the principle of direct lift. They are mostly traditional devices evolved before the industrial era, though in some of them improved mechanisms have been incorporated for more efficient utilization of the animal power. High velocity pumps are unsuitable for use with animal power as it is not practical to maintain a nearly constant speed of operation, using animals.

The main disadvantage of animal power is that animals need feed throughout the year while the irrigation period is limited to about 100 to 150 days. In many cases an appreciable part of the farm area is to be deployed to grow fodder. However, agricultural residues often provide for a substantial part of the feed and fodder requirements of the farm animals. It is always advantageous to utilize the same animals for tillage and other draft work on the farm, post harvest duties like threshing and milling and in transporting the farm produce. In traditional rural households animals often form an important part of the village economy. They produce by-products such as leather, milk, meat, and the dung used as a manure and sometimes as fuel for cooking. In a farming system in which animals provide the main means of draft power, their deployment in water lifting has the advantage of utilizing their energy during periods when they are not required for draft work or post harvest duties.

8.2.1 Power Capabilities of Draft Animals

Animals commonly used to operate water lifting devices are bullock/ox, buffalo, camel, donkey, mule and horse. Typical power capacities and operating speeds of these animals are presented in Table 8.3.

TABLE 8.3 Power Capacities and Operating Speeds of Commonly Used Draft Animals

Animal	Weight kg	Draft force kg	Power hp	Typical operating speed m/s
Bullocks/ox	400–900	60–80	0.3 to 0.6	0.4 to 0.7
Buffalo	500–900	60–100	0.6 to 1.3	0.5 to 1.0
Camel	500–1000	80–100	0.5 to 0.9	0.7 to 1.2
Donkey	150–300	20–40	0.1 to 0.6	0.6 to 0.8
Mule	350–500	40–60	0.3 to 0.7	0.8 to 1.0
Horse (medium size)	500–1000	50–100	0.6 to 1.0	0.8 to 1.2

Based on Fraenkel (1986)

Draft animals work best when subjected to a steady load which matches their pulling capacity. Cyclic loading such as is experienced when a pump is driven by a crank is not very suitable in animal power operation. Animals also need rest while in operation. Hence, it is common practice to work them on about three-hour shifts, with a rest in between. The total period of working is about 8 to 10 hours per day.

The commonly used animal powered water lifts are described in the following pages. Like manually operated water lifts, animal operated water lifts are available for use under low, medium and high head situations.

8.2.2 Low-Head Water Lifts

Circular Mot (Baldeo Balti)

The circular mot or *Baldeo balti* is an adaptation of the manually operated oscillating trough for animal operation (Fig. 8.19). It is used for lifts upto 1.5 m. The length of the rope passing over the overhead pulleys is so arranged that when one trough, which is filled with water, is rising up, the other is lowered down empty.

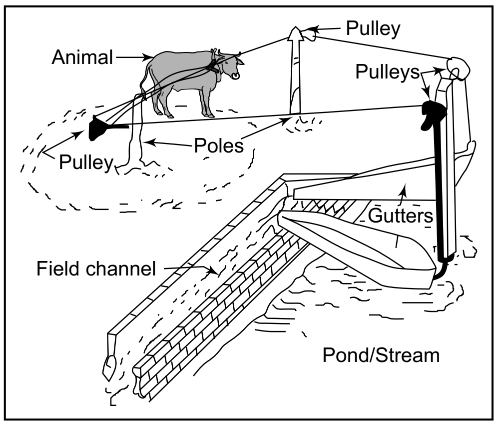


Fig. 8.19 Schematic view of a *baldeo balti*

Water Wheels

Water wheels are commonly used to lift water from sources where the lift is within 1 m. The paddle-wheel (Section 8.1) can be adopted for operation with small animals, including a single donkey (Figs. 8.20 and 8.21). The power transmission mechanism comprises a pair of gears, a vertical shaft and a wooden beam to which the animal is hitched. The gears are in the form of wheels to which spokes (short cylindrical rods) are fixed. One of the gears is fixed to the end of a horizontal shaft on the water wheel, and the other to the bottom of the vertical shaft. The number of teeth in each of the wheels is fixed to obtain the desired operating speed. The animals follow a circular path around the wheel. It is common practice to blind-fold camels, buffaloes, and donkeys in order to eliminate the need for constant attention by an operator. The operator could engage himself in other farm operations, including harnessing of the irrigation stream.

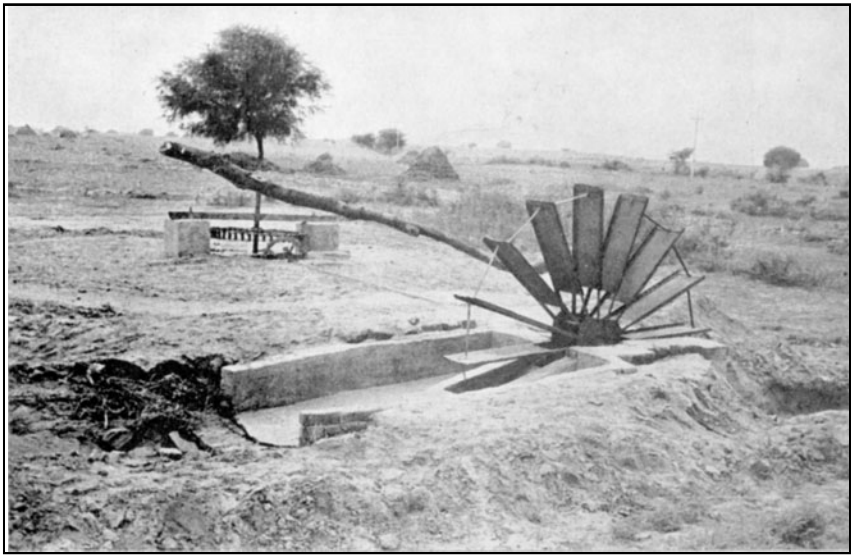


Fig. 8.20 View of a water wheel (Jalar) which could be operated by a pair of work animals (bullocks/buffaloes) or a camel. Note the masonary trough at the outlet head of the field channel

Animal Driven Water Wheel (Jalar)

The animal-driven water wheel, frequently called *jalar* in north India, is commonly used to lift water from canal water courses which run below the level of the irrigated fields. The lift is usually limited to about 1.2 m. The device consists of small sheet-metal paddles mounted radially on a horizontal shaft (Fig. 8.21). The wheel works in a close-fitting concave masonry trough constructed at the end of the water course or its branch. The wheel is driven by a bullock-gear drive, similar to that of a Persian wheel. The wheel, when rotated, pushes water into a trough at the inlet of the field channel. The device is efficient at low lifts.

Sakia

Sakia is a sophisticated water wheel used to lift water from a ditch to an adjacent crop field. It is the most popular water lifting device in Egypt, where about 52 per cent of the Egyptian farmers rent, share, or own one. The wheel of the *sakia* consists of several individual compartments which curve

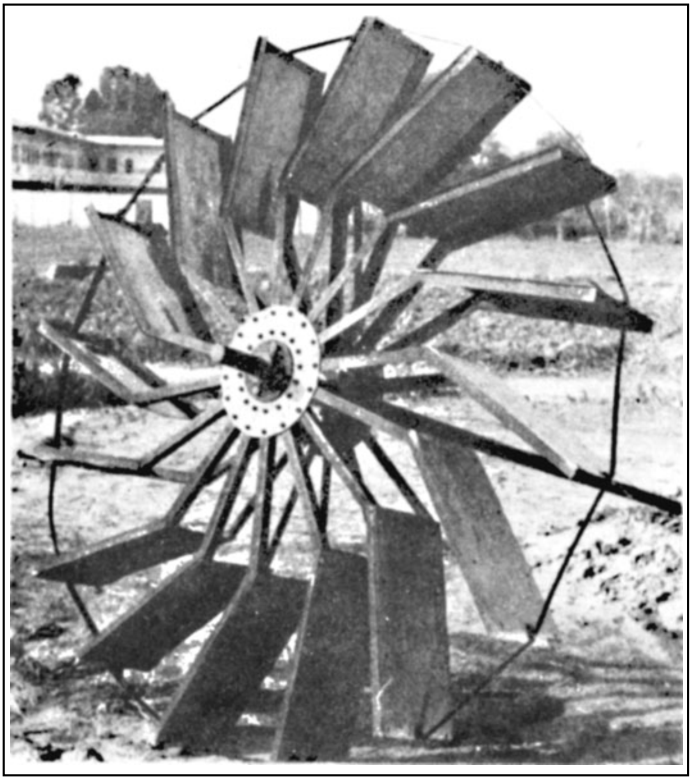


Fig. 8.21 Close view of the wheel of an animal operated paddle wheel (*Jalar*) shown in Fig. 8.20

inwards towards the centre of the wheel (Fig. 8.22). Each compartment has a large inlet at the outer circumference of the wheel and an outlet at its hub. These compartments are called *kawadies* (*kados*), and the number and shape of the *kawadies* will vary from one *sakia* to another. As the *sakia* turns, a *kados* submerges and fills with water. As the wheel completes its rotation, the filled *kados* is raised out of water and the water trapped in it flows away from the inlet, on the outer circumference of the wheel, towards the central outlet, which is now lower than the rest of the compartment. The water discharges from the outlet at the hub of the wheel into a channel which will carry it to the fields.

Sakias are usually made of galvanized steel. They have diameters varying from 2 to 3 metres and include 4 to 6 *kawadies*. They are driven by draught animals including bullocks, buffaloes and sometimes donkeys. A significant point in the water-wheel-type lifting design of the *sakia* is that it does not require the water to be lifted significantly above the required elevation. The *sakia* has an efficiency of about 45 per cent, which is higher than other water-wheel-type lifting machines.

The discharge of a *Sakia* can vary widely, depending on its diameter, width, static lift, speed of revolution, and how well it is maintained. The discharge of a 3-metre diameter *sakia*, lifting water approximately one metre, is between 72,000 and 75,000 1/h. The speed of the wheel is approximately 3 revolutions per minute.

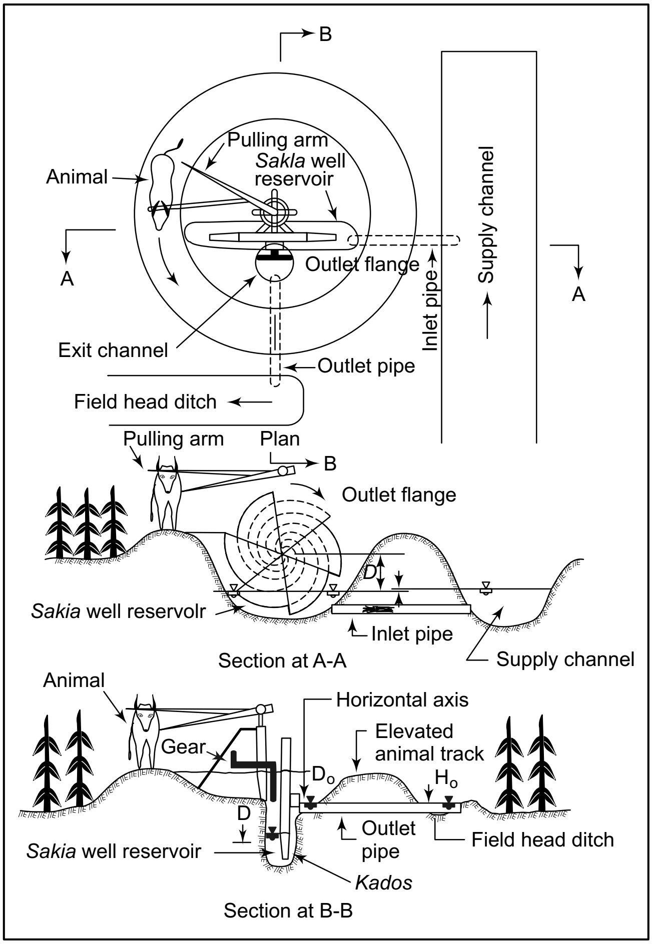


Fig. 8.22 Views of a typical *sakia* installation
Adapted from: Horsey (1983)

8.2.3 Medium-Head Water Lifts

In this group are included water lifting devices suitable for 4 to 10 m lifts. These include the most popular animal operated water lifts like the Persian wheel, chain pump and rope-and-pulley operated self-emptying buckets.

Persian Wheel

The bucket chain or Persian wheel is probably the most popular amongst indigenous water lifts for medium-head operation. It is extensively used in India and other developing countries. The device, as mentioned earlier, consists of a chain and a series of buckets mounted on an open spoked drum provided with a suitable driving mechanism. Traditional types of Persian wheels used earthenware pots and jute or coir rope for the endless chain. Modern Persian wheels (Fig. 8.23) use sheet-metal buckets and hook chains made of mild steel bars. The capacity of the bucket ranges from 7 to 10 litres. Two parallel loops of chain, joined by spacing bars and having metal or earthenware pots attached to them at intervals, pass over the drum and loop into the water in the well. A horizontal shaft extends from the central axis of the drum to a small vertical cog-wheel or gear. The teeth of this vertical gear mesh with those of a large horizontal wheel gear. Fitted to the shaft of the horizontal gear is a long horizontal beam to which the draught animals are hitched. In some models, the long horizontal shaft is eliminated and the animals go around the well instead of moving on a separate platform.

Fig. 8.23 A traditional Persian wheel operated by a pair of bullocks

When the Persian wheel is operated, the bucket-drum revolves. The buckets at the lower end of the chain get filled with water and are carried to the top with their open mouth upward. The buckets get filled by dipping into the water in the well. Therefore, a certain minimum length of chain must remain immersed in water. When the buckets pass over the top of the drum, they spill their contents into a trough, from where it is conveyed through the irrigation channel. Each bucket has a small hole at the bottom for drainage when the water lift stops working. A ratchet arrangement prevents the wheel and buckets from being turned backward by the weight of the filled buckets.

The Persian wheel lifts water over a height of upto about 10 m. But its efficiency is considerably reduced when the lift exceeds 7.5 m. With increase in height, the number of loaded buckets is increased and this puts a heavy strain on the animals.

At places where the depth to water level does not exceed about 5 m, two rows of buckets, mounted on separate drums and fixed on a common shaft, could be used with advantage. This arrangement almost doubles the discharge.

In a Persian wheel, water is lifted considerably above the ground level before it is discharged from the buckets into the receiving trough. The extra energy required in this is especially significant when the water table is close to the ground or when the device is used to lift water from ponds or streams.

Animal Driven Chain Pump

The chain pump described in Section 8.1.2 can be easily adapted for operation by animals (Fig. 8.24). In case of animal driven chain pumps, a drive mechanism similar to the one used in Persian wheels can be adopted. The animal operated chain pump is usually equipped with a 15 cm diameter pipe and matching disc washers. The advantage of the chain pump is that it eliminates the extra lift which is encountered in the Persian wheel in lifting the filled buckets over the bucket wheel. In a chain pump, the water is discharged directly into a trough at the ground surface. However, the chain pump has not become as popular as the Persian wheel since it needs greater maintenance, i.e. replacing worn washers and the occasional removal of kinks in the chain.

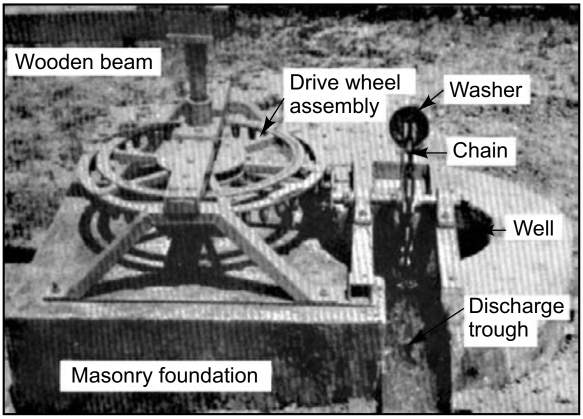


Fig. 8.24 The drive mechanism and discharge end of an animal operated chain pump installed in an open well

Rope-and-Bucket Lift with Self-Emptying Bucket

The self-emptying type rope-and-bucket lift is suitable for operation with a pair of average size draught animals. The device consists of a sheet metal or leather bucket of about 100 to 150 litres capacity. At the bottom of the bucket is fixed a leather tube or spout (Fig. 8.25). The bail of the bucket is attached to a heavy rope which passes over a pulley (Fig. 8.26).

A second, lighter rope is fastened to the lower end of the spout. This second rope passes over a roller fixed to the lip of the receiving trough, at the ground surface. Both ropes are tied together and then attached to the bullock yoke. Their lengths are so adjusted that the spout folds up along the side of the bucket while it is being raised from the well.

When the bucket reaches the top of the well, the spout follows its own rope over the roller, while the bucket continues to rise upward towards the pulley. When the spout is extended downward, water is discharged through it into the trough. After the water is discharged, the bullocks are made to walk up the ramp to the place of starting.

The self-emptying bucket has the advantage that it saves the labour of one man. However, some time is lost in operation when the animals are made to walk back on the ramp. A toggle is often used to disengage the rope from the yoke, after the bucket is empty. The bullocks could then be made to turn around and walk up the ramp, thus speeding up the operation to some extent.

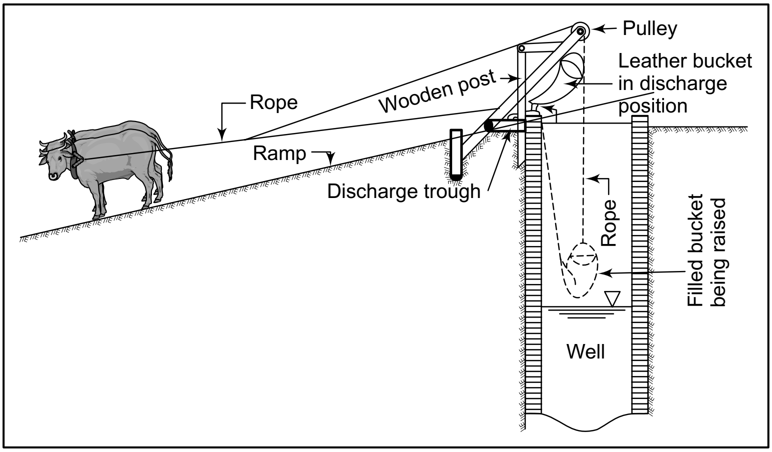


Fig. 8.25 Schematic sketch illustrating the principle of operation of a rope-and-bucket lift, using a self-emptying leather bucket

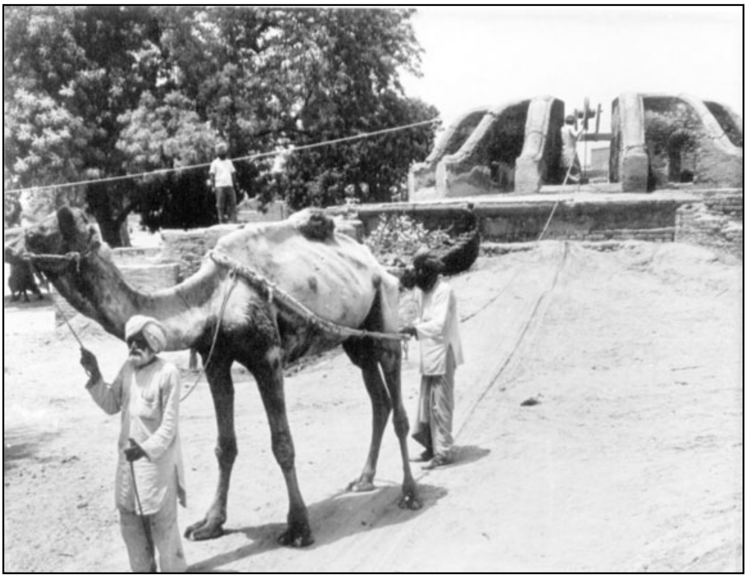


Fig. 8.26 A camel operating a rope-and-bucket lift working on rope and pulley system in an open well. Note the pump platform and the pulley blocks for simultaneous operation of several buckets in the high yielding open well

Circular Two-Bucket Lift

The device uses two buckets which are alternatively raised, emptied, lowered and filled. While one bucket is filled and lifted, the other is lowered empty into the well. A rope and pulley arrangement along with a central rotating lever permit reciprocating action while the bullocks move on a circular path (Figs. 8.27 and 8.28). The rope arrangement is such that at no time both the buckets are filled and drawn together. Each bucket is of about 70 litres capacity. It is provided with a flap valve at the bottom for filling. As the bucket is lowered into the water in the well, the valve opens and the bucket is filled automatically. When it moves up, the weight of water keeps the valve closed. Two vertical rods fixed to the well lining wall guide the buckets in their up and down movement. When the bucket reaches the top, it is tilted automatically due to the loop on the rod and the water is discharged into the receiving trough.

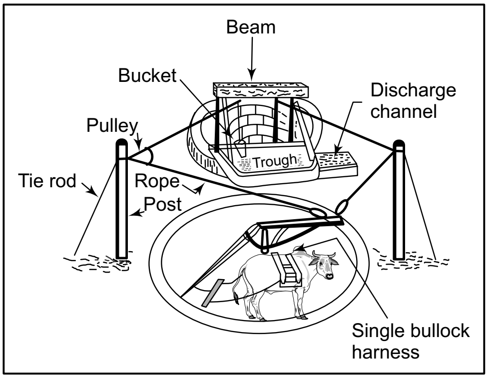


Fig. 8.27 Schematic view of a circular two-bucket lift (*charsa*), showing the arrangement of rope and pulleys and one of the self-emptying buckets

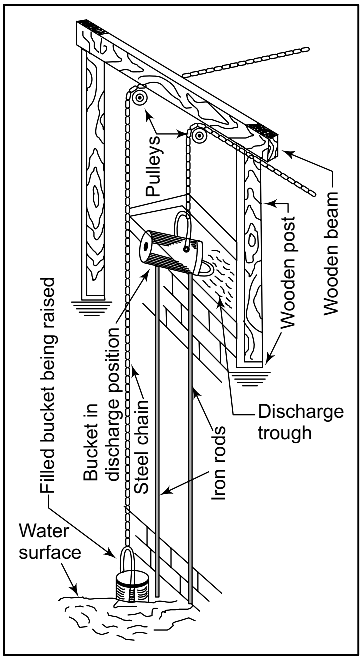


Fig. 8.28 Close view showing the buckets and self- emptying mechanism of a circular two-bucket lift (Fig. 8.27)

8.2.4 High-Head Water Lift

Devices suitable to lift water from depths greater than 10 m may be grouped in this category. From the point of view of suitability for irrigation, the only indigenous water lift for deep wells is the rope-and-bucket lift operated by cattle.

Rope-and-Bucket Lift

The rope-and-bucket lift consists of a bucket or bag of about 150 to 200 litres capacity, made of leather or galvanized-iron sheet. The bucket is fixed on a stout iron ring with an iron frame work at the top, and is tied to a long rope. The rope passes over a pulley set on a wooden frame work fixed on top of the well. A pair of bullocks, buffaloes or a camel, hitched to the other end of the rope, provide the power to lift the bucket. The animals, while pulling up the full bucket, walk down on an earthen ramp sloped at an angle of 5 to 10 degrees, thereby taking advantage of their body weight to exert the necessary force to lift the bucket.

The rope-and-bucket lift can be worked by one pair of bullocks or buffaloes or a camel and two men. More commonly, however, two pairs of bullocks or buffaloes or two camels, and three men are used, one man for emptying the bucket and two others for driving the animals. When two pairs of draught animals are used, one pair walks up the slope while the other is drawing up the bucket. The device may be operated singly or in multiples of two or more working simultaneously, depending on the yield of the well and the requirement of irrigation water.

8.3 POSITIVE DISPLACEMENT PUMPS

A pump is a mechanical appliance used to increase the pressure energy of a liquid, in order to lift it from a lower to a higher level. This is usually achieved by creating a low pressure at the inlet and a high pressure at the outlet ends of the pump. Thus, the principle of working of a pump is distinctly different from the indigenous water lifts in which water is lifted by displacement through buckets, water wheels or screws.

Pumps are classified into two basic groups, based on the method by which energy is imparted to the fluid. They are: (i) positive displacement pumps, and (ii) variable displacement pumps. There are various types in each group. In a positive displacement pump, the fluid is physically displaced by mechanical devices such as the plunger, piston, gears, cams, screws, diaphragms, vanes or other similar devices. In a piston pump, the pump chamber is alternately filled and emptied by the suction and discharge created by the moving piston. The movement of the piston is derived from a crank and connecting rod mechanism. Automatic valves control the flow of liquid into the cylinder and out of it Fig. (8.29). The volume of water delivered by a positive displacement pump is constant, regardless of the head against which it operates (Fig. 8.30). It is varied only by a change in the speed of the piston.

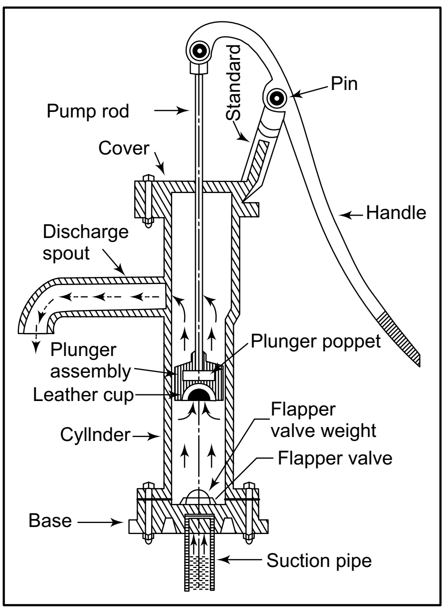


Fig. 8.29 Sectional view of head assembly of a shallow-well lift pump

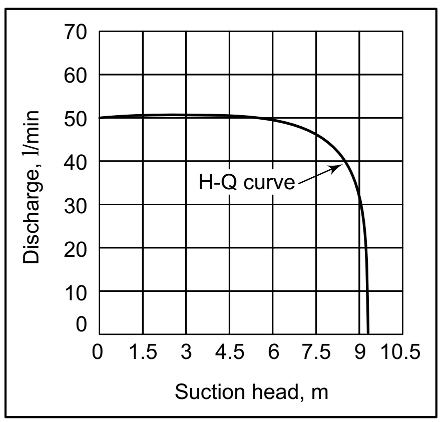
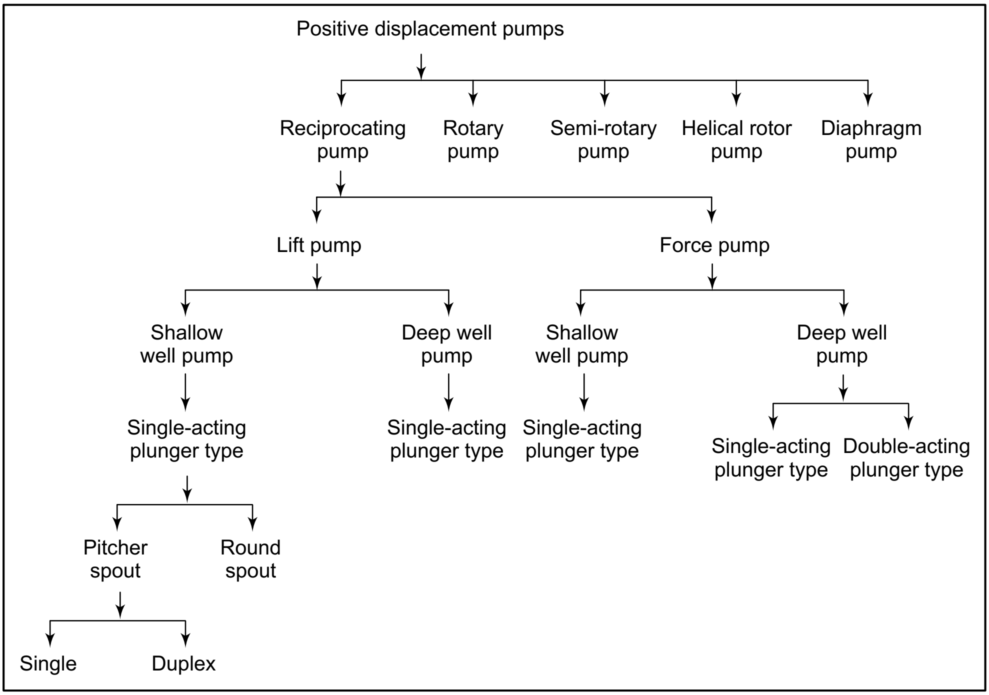


Fig. 8.30 Relationship between suction head and discharge in a positive displacement pump

On the other hand, the discharge of a variable displacement pump varies inversely as its pressure head. Further, its discharge characteristics are profoundly influenced by the diameter and speed of the rotating member or impeller. However, they have large discharge capacities and are commonly used in irrigation.

Positive displacement pumps have a large number of moving parts and require greater attention in maintenance. They are of low speed. As their discharge capacities are small, they are not popular in irrigation and drainage. However, they are extensively used in domestic water supply systems, well drilling and other special applications.

The common types of positive displacement pumps are shown schematically as follows:



Pump Discharge in Relation to Design Dimensions and Operating Characteristics

The basic relationship between pump discharge and design dimensions may be expressed as follows:

(i) Area swept by the pump piston $a = \frac{\pi}{4} d^2$

in which, d = diameter of the piston

(ii) Volume swept per stroke $V = a\,s$

in which, s = stroke (length of piston travel)

(iii) Volumetric efficiency η_{vol} = % swept volume that is actually pumped

(iv) Discharge per stroke $q = \eta_{vol} V$
(v) Pump discharge rate $Q = n\,q$
in which, n = number of strokes per minute of the piston

Volumetric efficiency is usually expressed as a decimal fraction and is sometimes called coefficient of discharge.

Slippage. Slippage of reciprocating type pumps is the difference between the swept volume and the output per stroke:

Slippage $X = V - q$

Slippage arises partly because the valves take time to close. They may be still open when the piston starts its upward travel. It may also remain open because of back leakage past piston or valve seats. Slippage may range from 0.1 to 0.2 times V. It tends to be more with shorter stroke pumps and with higher heads. With high discharge rates at low heads, the upward flow of water in the pipe may be continuous with both valves remaining open for a part of the downstroke. The discharge continues for a part of the downstroke and the full upstroke. In such situations the slippage is negative i.e. the pump discharge is more than its swept volume.

Pistons and Valves

Figures 8.29 and 8.32 show the details of common types of pistons and valves. Numerous forms of packings are used to prevent leakage past a piston or plunger. Cup leathers are usually used for packing. Suitable grades of leather commonly impregnated with 'meatsfoot' oil boiled from hooves of cattle could function satisfactorily for several years in smooth brass or PVC cylinders. Various plastic based synthetic leather materials are also used for seals, which are usually more consistent in their performance than leather. The pressure of water acting inside the cup presses the leather outwards, thus preventing leakage.

All reciprocating pumps use check valves (also called non-return valves) which allow water to flow one way and prevent return flow. Basically there are three types of check valves:

(i) Flexible valves that are normally in a closed position, but open by being bent or deformed when pressure is applied.
(ii) Hinged valves.
(iii) Straight lift valves which rise vertically from their seats.

Valves are opened by the difference in water pressure across them, created by piston movement. They are closed by their own weight together with the weight of water over it. In some cases closing is assisted by a light spring. Valve springs are usually made of bronze to prevent corrosion. Alternatively, valves may be made of elastic material like rubber.

The prime requirements of a valve is a good seal when closed, minimum resistance to flow when they are open, rapid opening and closing and durability. Rubber or precision ground metal mating surfaces are necessary to ensure leak-proof valves. To ensure low resistance to flow when open and to provide for quick opening and closing, large port areas with as few changes in flow direction as possible, and a minimum of sharp surfaces which can cause turbulence, are essential. In general, the suction valve should have a port area at least two-thirds of the piston area, while the discharge valve (piston valve) should have an area at least half the piston area. Rapid opening and closing (to minimise back-leakage) depends on comparatively light weight for valves combnined with short travel distance. Since valves are subject to wear and tear, provision for replacement of valves and their seats is essential.

8.3.1 Reciprocating Pumps

A reciprocating pump consists of a piston or plunger working in close fitting cylinder. The movement of the piston displaces the water in the cylinder. The capacity of reciprocating pumps depends on the size of the cylinder chamber and the length and speed of stroke of the piston.

Reciprocating-type pumps are broadly classified into two types, namely, lift pumps and force pumps. *Lift pumps* are designed to pump water from the source to the level of the pump spout only (Figs. 8.29 and 8.31). They are used in locations where the water is to be delivered into a bucket, trough, tank or other receptacles at the pump location. They utilize atomospheric pressure to raise the water to the pump column. Such pumps are mostly manually operated. *Force pumps* are designed to pump water to a higher elevation than the pump body (Figs. 8.31 and 8.41). They are usually used to pump water from deep wells or to storage tanks in domestic water supply. They are similar in construction to lift pumps, except that they are enclosed at the top and hence can be used to force water to higher elevations.

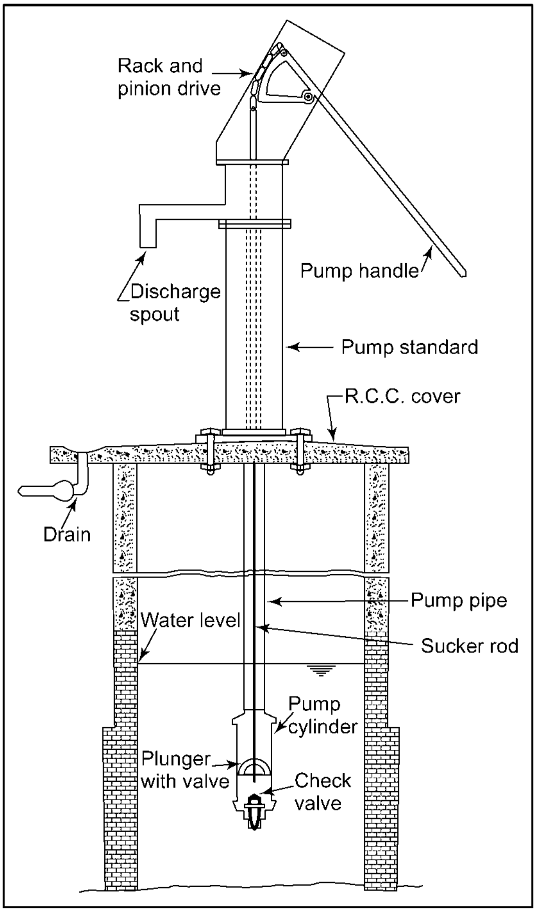


Fig. 8.31 An India Mark II* deep well force pump installed in an open well for drinking water supply

Single-Acting Plunger Pumps

Reciprocating pumps used in domestic water supply and small scale irrigation are usually of the single-acting plunger type. They consist essentially of a cylinder in which the plunger with a valve moves up and down.

* A major break through in hand pumps has been the development of India Mark II deep well hand pumps by M/s Richardson Cruddas (India) Ltd., 23 Rajaji Salai, Chennai 600001. It can be installed in tube wells/bore-holes of size 10 cm to 15 cm diameter for lifts up to 90 m with a discharge rate ranging from 12 to 24 litres per minute. Optimum water depth for operation of ordinary model is 28-32 m. For depths beyond 45 m, India Mark II Extra Deep Well Hand Pump was developed in 1986. The pump has become extremely popular in India and has been commended by UNICEF and approved by over 30 countries by 1988.

Shallow Well Lift Pump

In a shallow well lift pump, the pump body, containing the cylinder and plunger, is located at ground level (Figs. 8.29 and 8.34). The plunger when moved up and down by the movement of the pump rod, displaces air from the cylinder through the non-return valve at its bottom. On the downward stroke, the bottom valve closes and the water passes through a second non-return valve in the plunger. On the next up-ward stroke, this water is forced out through the open spout while a second intake is drawn through the bottom of the cylinder. Water is thus raised to the pump head and discharged through a spout.

Theoretically, the pump can lift water from a height upto one atmosphere or 10.33 m. But, in practice, the height reached does not exceed 8 m due to friction in the pipeline and other losses. The pump discharge drops greatly beyond a suction limit of 6 m (Fig. 8.30).

Numerous forms of packings are used to prevent leakage past a plunger. Cup leathers (Fig. 8.32) are usually used for packing. The pressure of water acting inside the cup presses the leather outwards against the cylinder, thus preventing leakage.

Deep Well Lift Pumps

The deep well lift pump is designed to lift water from depth below 7 m and deliver it at the pump spout (Fig. 8.31). The pump cylinder, with its plunger and valves, is located in the well within the suction limits (< 7 m). Most commonly, however, the cylinder is submerged below the static water level in order to prevent loss of priming. The plunger is connected to the pump handle or other operating device like a mechanically powered crank-shaft. The details of construction of a deep-well reciprocating pump are illustrated in Fig. 8.31. The principle of suction is the same as for a shallow well reciprocating pump. The upward stroke of the plunger creates a vacuum in the pump cylinder, resulting in suction. During the downward stroke, the delivery valve on the plunger body opens and water is forced above the plunger. In the next upward stroke, water is forced up through the delivery pipe, and another charge of water fills the space between the valves. The cycle is repeated in each pair of strokes.

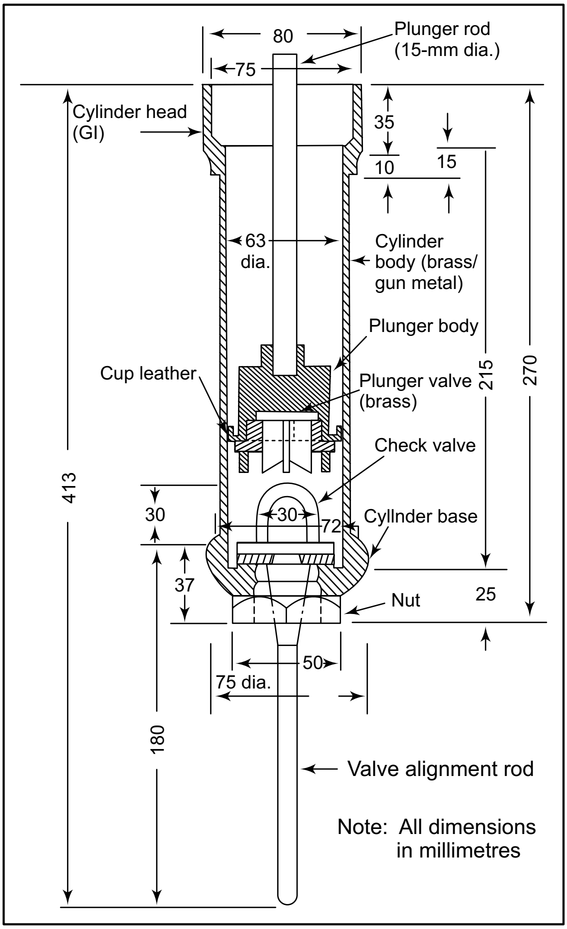


Fig. 8.32 Sectional view of the cylinder and plunger of the deep well lift pump shown in Fig. 8.31

Deep well reciprocating pumps may be manually operated or mechanically driven. Manually operated pumps are suitable only for lifts upto about 35 m, beyond which manual pumping becomes progressively difficult due to the increasing weight of the water column and the connecting rod that must be lifted with each upward stroke. (Special designs of deep well pumps are available for depths up to 90 m).

Installation of Mechanically Powered Deep Well Reciprocating Pumps

Deep well reciprocating pumps operated by engines or electric motors are provided with a suitable working head at the well top. The working head consists of a crankshaft and connecting-rod assembly provided with a cross head to which the pump rod is attached. The crankshaft changes the rotating motion of the engine to reciprocating motion at the piston. As the reciprocating pump is to work at low speeds, a gear box may be provided with the working head. Alternatively, the necessary speed reduction may be obtained by adjusting the sizes of the pulleys on the engine or the motor and the crankshaft. Usually, power is transmitted to the working head by a belt drive. The working head is often provided with fast and loose pulleys.

The engine or motor is installed close to the well, on a level foundation. The working head is fixed on a sturdy frame made of angle iron or wooden joists placed over the top of the well. Both ends of the shaft of the working head are supported on ball bearings.

Types of Reciprocating Pumps Based on Construction and Operating Features

While the basic principles of operation apply to all types of reciprocating pumps, there are many modifications in design which adapt them to specific uses. Reciprocating pumps may be either single-acting or double-acting.

Single-Acting Pumps

Single-acting reciprocating pumps (Fig. 8.29 and 8.31) have one discharge stroke for every two strokes of the piston. Thus, water is delivered during alternate strokes of the piston. The flow through the delivery pipe is, therefore, intermittent. An air vessel may be fixed over or near the delivery valve to provide a steady discharge (Fig. 8.33). During the delivery stroke of the piston, the air in the air vessel is compressed to a greater pressure than the head of water at the bottom of the delivery pipe. During the suction stroke, the pressure of the air in the vessel maintains the flow of water through the delivery pipe, thereby ensuring nearly continuous discharge.

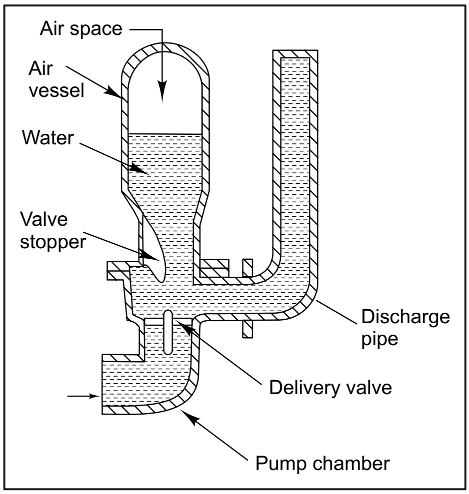


Fig. 8.33 Air vessel for being fitted to the delivery side of a single-acting pump

Manually Operated Twin-Treadle Pump

A foot-operated twin pump (Fig. 8.34) developed by RDRS, Bangladesh*, called twin treadle pump, is considered as a major contribution to small scale lift irrigation through low-cost shallow tube wells.

* Rangpur Dinapur Rehabilitation Service, Lutheran World Federation, GPO, Box 618, Ramna, Dhaka-2 Bangladesh.

The main features of the pump are the twin plunger pump and the use of the body weight of the operator in pumping.

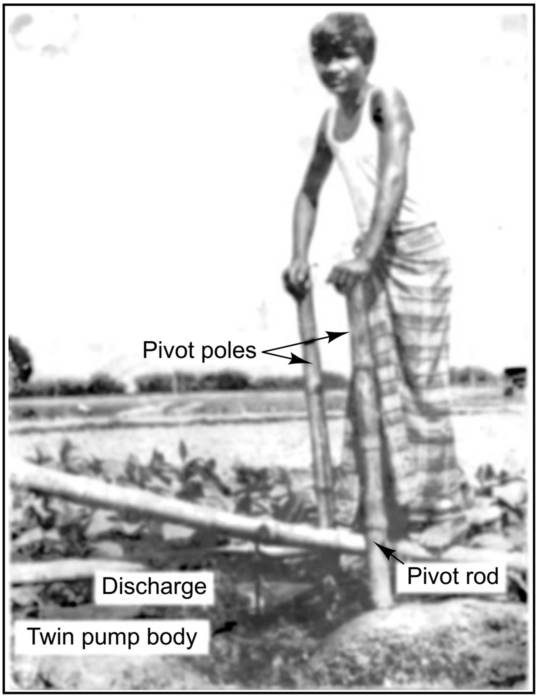


Fig. 8.34 A twin-treadle pump in operation on a tobacco farm near Dinapur, Bangladesh. The pump is adapted for operation even by young boys and rural women.

The components of the pump are shown in Fig. 8.35. The suction pipe at the bottom of the pump is connected to the water source, which may be a tube well or an open-water source, such as an open well, stream, or pond. The pump sucks water up the suction pipe and into a manifold that is connected to the two pump cylinders. Each cylinder is equipped with a foot valve that prevents the back-flow of water from the cylinder to the suction pipe during the return stroke of the pump. The foot valve could be a simple rubber flap made from a used inner tube of a truck tyre. The pump plunger consists of two round discs fastened to a rod and moulded rubber or PVC cup or bucket. The upper disc has holes that allow water to pass through the plunger during the downward return stroke. On the upward pumping stroke, the bucket is pressed against both the lower disc and the cylinder wall. This provides a seal that prevents water from passing by the piston. It also creates a partial vacuum that sucks water into the cylinder from the manifold and the suction pipe. The plunger assembly is easy to fabricate with simple tools. It utilizes the buckets of standard domestic water hand pumps, which are widely used in developing countries. The plunger rods are connected to the treadles (generally bamboo poles) by means of a hinged joint.

By placing the pivot of the treadles at a considerable distance (about 1 m) from the pump cylinders, the motion of the plunger will not deviate significantly, from the centre-line of the cylinder, thereby,

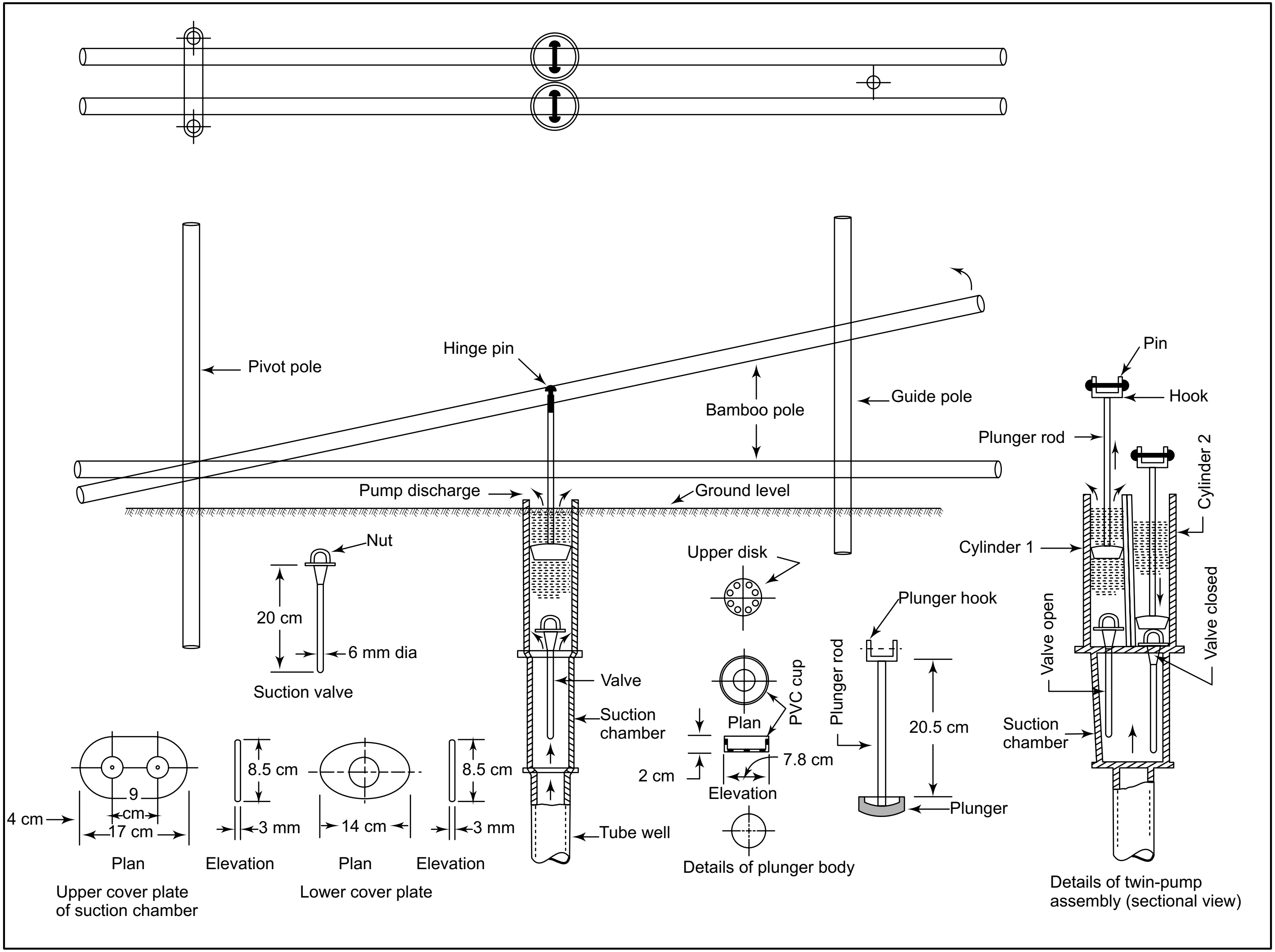


Fig. 8.35 Components of a manually operated twin-treadle pump

avoiding problems of wear of the bucket. The length of the treadle is sufficient to enable the operator to vary the position of his feet, to achieve comfortable and efficient operation. The wooden posts to which the treadles are pivoted allow the operator to balance himself. The pump cylinders are generally made from standard sizes of steel pipes or of cast iron. It could also be made of mild steel sheet (16 gauge), using a conventional sheet metal roller.

The basic pump design has been modified, since its initial development in early 1980s, to suit different types of water sources, irrigation application, and farmer preferences with respect to materials and operation. For example, the use of spout is optional. The earlier design used a rope-and-pulley arrangement for operating the treadles. This was subsequently found unnecessary.

The twin treadle pump has a capacity of about 3 litres/second for a 2 metre lift and 2 litres/second for a 4 m lift.

Rower Pump

The rower pump (Fig. 8.36) was developed in Bangladesh in 1979 by the Mennonite Central Committee. Its name is derived from the fact that it is inclined at an angle of about 30º to the horizontal and operated with a rowing action. The rower pump is essentially a shallow tube well suction pump usually installed with a 4 cm diameter PVC or mild steel pipe filter. The pump cylinder is made of an extruded PVC pipe. The plunger uses a leather cup seal, impregnated with paraffin wax, which is mounted on aluminium piston components. The check value is a moulded plastic component with a simple flap valve of inner tube rubber. A distinguishing feature of the rower pump, which makes it more efficient than the conventional hand pump, is the provision of a 4.5 litre capacity air chamber on the suction side below the check valve. The air chamber smoothens the flow into the pump.

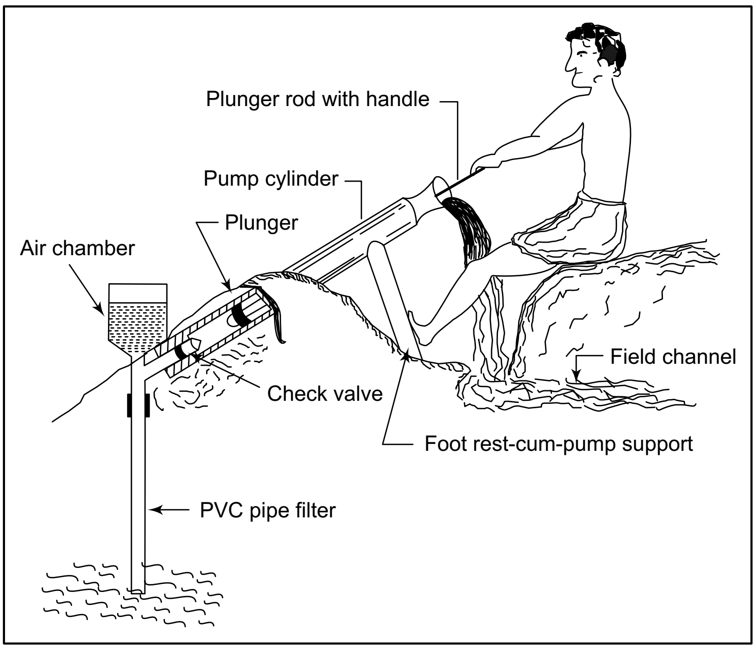


Fig. 8.36 Schematic sketch illustrating the construction and operation of the rower pump

The rower pump can be used to lift water from a depth of 1 to 8 m. The pump has only one moving part, the plunger, thus reducing the friction losses to the minimum. The cup seal is the only part which can wear. These design features make the rower pump suitable for use in small scale irrigation.

Installation and Operation

The pump head is buried in the ground. Two operating positions are possible:

1. Sitting for irrigation purposes
2. Standing for drinking water use.

For use in domestic water supply a masonry trough at the outlet is desirable. For irrigation use water flows directly into the field channel. The installation requires only basic skills and PVC joining techniques. The pump is susceptible to improper installation. It should be safely secured into the ground and the operating position should be correct. The PVC cylinder is subject to deterioration due to the UV rays in sunlight. Hence, it is desirable to cover the exposed part of the pump cylinder with bamboo or other material.

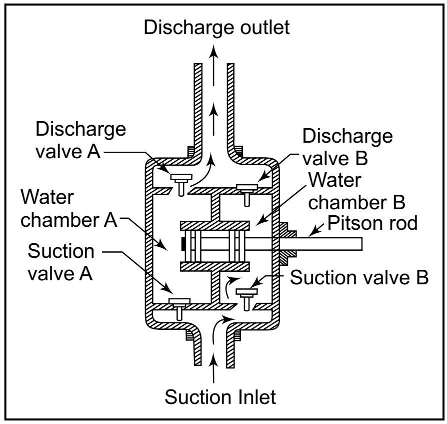


Fig. 8.37 Sketch illustrating the principle of working of a double acting reciprocating pump

A common maintenance requirement is the frequent attention needed to the leather cup seal. This is easy as the piston can be extracted by simply pulling it out of the cylinder. The piston assembly should be re-tightened occasionally because the leather cup seal works itself loose.

The manufacture of rower pumps require a relatively well equipped workshop with facilities for machining, PVC extrusion, plastic moulding, aluminium die casting and aluminium flaring. Rower pump is a low cost device.

Double Acting Pumps

These are constructed with the piston and valves so arranged that water is pumped on both the inward and outward movements of the piston (Fig. 8.37). Though the arrangement is more commonly used in lift pumps, it is also sometimes incorporated in force pumps.

Duplex Pump

These pumps consist of a pair of pump chambers and plungers designed to pump a continuous stream of water with minimum pulsation (Figs. 8.35 and 8.38). The working of the pump is so arranged that when there is a discharge stroke of the plunger in one chamber, there is suction in the other.

Animal Powered Reciprocating-Type Duplex Pump

The animal powered duplex reciprocating pump developed by Khepar *et al*. (1975) is specially suitable for pumping water from shallow tube wells (Fig. 8.38). The conventional bullock gear, of the type commonly used with Persian wheels, is used to transmit the power of the pair of draft animals to

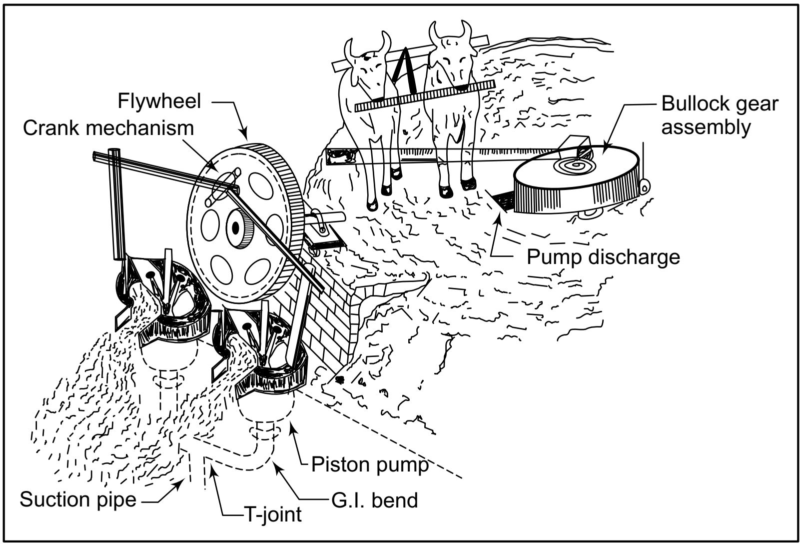


Fig. 8.38 Schematic sketch illustrating the construction and operation of an animal powered reciprocating type duplex pump

Fig. 8.38(a) An animal operated duplex reciprocating pump in operation on a shallow tube well

operate the pump (Fig. 8.38(a)). The pumping unit consists of a pair of ordinary piston pumps. Each pump has a cylinder diameter of 30 cm, with pistons having a stroke of 11 cm. The suction ends of the two pumps are connected by bends to a T-joint to which a common suction pipe is connected. The suction pipe, which is smaller in diameter than the tube well, is lowered into the well.

The power transmitted through the bullock gear (Fig. 8.38 (b) & (c)) is applied to operate the pistons through a flywheel, to which are connected the pump rods. The linkage mechanism is designed to obtain the desired piston stroke. The drive provides one discharge stroke in each pump for each

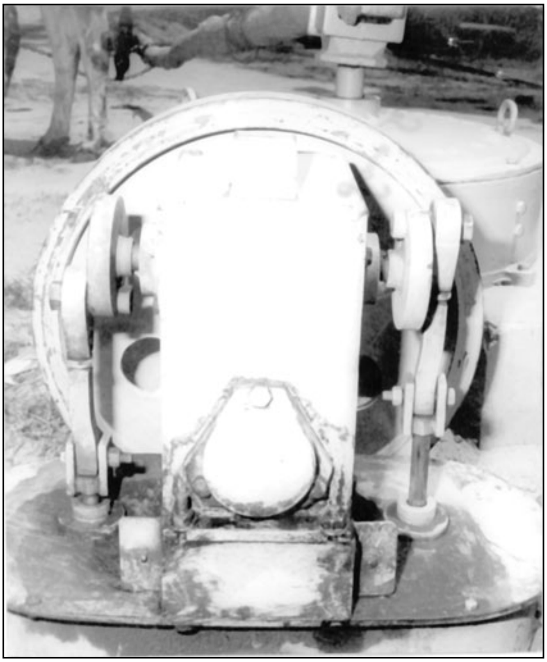


Fig. 8.38(b) Close view of the power transmission system in the animal operated duplex reciprocating pump shown in Fig. 8.38(a). Note the flywheels and power transmission mechanism on either side. In the centre is the gear box for speed control. The shafts at the bottom are linked to the connecting rods of the piston pumps on either side.

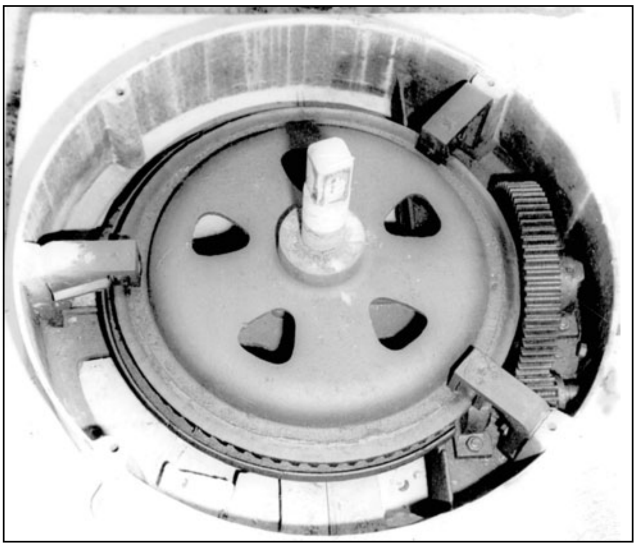


Fig. 8.38(c) An exposed view of the gear box of the power transmission mechanism of the animal operated duplex reciprocating pump

revolution of the flywheel. The suction and discharge strokes of the pair of pumps alternate with each other, i.e. when there is suction in one pump there is discharge in the other. The flywheel provides the inertia required for the smooth running of the pump.

The animal operated pump is suitable to lift water from shallow tube wells and open wells, when the depth of pumping water level does not exceed 6 m from the ground surface. It gives a discharge of about 7 l/s, against a head of 4 m.

8.3.2 Force Required to Work a Reciprocating Pump

The force required to lift the piston will be the weight of the piston and pump rods, plus the weight of the column of water having a cross-sectional area equal to the area of the piston and a height equal to the head. There is also a dynamic head which is the force required to accelerate these masses. If the acceleration is small, the dynamic head can be neglected.

Let, a = area of cylinder, m^2

l = length of stroke, m

h = total height through which water is raised, m

P = force required to lift the piston (neglecting friction and weight of the piston and connecting rod), kg

w = specific weight of water, kg/m^3

Then, Weight of water raised in one stroke = $w\ a\ l = 1000\ al$

$$\text{Work done in one upstroke} = 1000\ a\ l\ h = P\ h \tag{8.2}$$

Therefore,

$$P = 1000\ a\ l$$

Hence, P is independent of the diameters of the suction and delivery pipes, if friction is neglected.

If the pump rod is connected to a lever, as in a hand pump, the downward force required to lift the pump rod will be reduced by the ratio of the leverage. However, the distance the hand of the operator will have to move, compared with the stroke, will be proportionately increased. A problem with hand lever pumps is wear and tear resulting from hammering in operation. Hammering can be caused by worn pivots and bearings causing backlash, which will cause impacts if the operator lifts the handle too rapidly. Further, the need for the operator to constantly raise and lower a heavy lever wastes energy. Hence, rotary drive pumps in which the piston is driven by a crank from a rotating drive wheel are easier to operate. However, rotary drive pumps are relatively heavier and expensive due to their massive flywheel and crank mechanism and the supporting column which is required.

Example 8.1 A single-acting reciprocating pump has a piston of diameter 10 cm and stroke of 20 cm. The piston makes 40 double strokes per minute. The suction and delivery heads are 5 m and 10 m, respectively. Find (i) the discharge capacity of the pump in l/min, (ii) the force required to work the piston during the suction and delivery strokes, if the efficiency of the suction and delivery strokes are 50 and 60 per cent, respectively, and (iii) the hp required by the pump for its operation.

Solution

(i) Area of piston, $a = \frac{\pi}{4}d^2 = \frac{3.14}{4} \times \frac{10}{100} \times \frac{10}{100} = 0.008 \text{ m}^2$

Volume swept by piston per stroke $= al = 0.008 \times \frac{20}{100}$

$= 0.0016 \text{ m}^3$

Discharge of pump $= 0.0016 \times 40 = 0.064 \text{ m}^3\text{/min}$

$= 0.064 \times 1000 = 64$ l/min

(ii) Average force in suction $= w \times a \times$ suction head $\div$ efficiency of delivery stroke

$$= \frac{1000 \times 0.008 \times 5}{0.50} = 80.0 \text{ kg}$$

Average force in delivery $= w \times a \times$ delivery head $\div$ efficiency of delivery stroke

$$= \frac{1000 \times 0.008 \times 10}{0.60} = 133.3 \text{ kg}$$

(iii) Horse power required by the pump

= Total force (suction + delivery) × Distance moved in m/min ÷ 4560

$$= \frac{(80.0 + 133.3)}{4560} \times 40 \times \frac{20}{100} = 0.374$$

Example 8.2 A double-acting reciprocating pump has a piston of 20 cm diameter, and a piston rod of 5 cm diameter which is on one side of the piston only. The length of the piston stroke is 30 cm and the speed of the crank moving the piston is 50 rpm. The suction and discharge heads are 5 m and 10 m, respectively. Determine the discharge capacity of the pump in l/min and the hp required to operate the pump.

Solution

Cross-sectional area of piston,

$$a = \frac{\pi d^2}{4} = \frac{3.14}{4} \times \frac{20}{100} \times \frac{20}{100} = 0.031 \text{ m}^2$$

Cross-sectional area of piston rod, a_1

$$= \frac{3.14}{4} \times \frac{5}{100} \times \frac{5}{100} = 0.00196 \text{ m}^2$$

(a) Force required to work the piston during 'in' stroke

(i) For suction $= w \times a \times$ suction head $= 1000 \times 0.031 \times 5$

$= 155$ kg

(ii) For delivery $= w\,(a - a_1) \times$ delivery head

$= 1000\,(0.031 - 0.00196) \times 10 = 290.4$ kg

Total force during 'in' stroke

$$= 155 + 290.4 = 445.4 \text{ kg}$$

(b) Force required to work the piston during 'out' stroke

(i) For suction = $w\,(a - a_1) \times$ suction head

$$= 1000\,(0.031 - 0.00196) \times 5$$
$$= 145.2 \text{ kg}$$

(ii) For delivery = $w \times a \times$ Delivery head

$$= 1000 \times 0.031 \times 10 = 310 \text{ kg}$$

Total force during 'out' stroke

$$= 145.2 + 310$$
$$= 455.2 \text{ kg}$$

Discharge during 'in' stroke = $a \times l \times$ rpm

$$= 0.031 \times \frac{30}{100} \times 50$$

$$= 0.465 \text{ m}^3\text{/min} = 465 \text{ l/min}$$

Discharge during 'out' stroke

$$= (a - a_1) \times 1 \times \text{rpm}$$

$$= 0.029 \times \frac{30}{100} \times 50$$

$$= 0.435 \text{ m}^3\text{/min}$$

$$= 435 \text{ l/min}$$

Total quantity of water raised by the pump

$$= 465 + 435$$

$$= 900 \text{ l/min}$$

hp required by the pump

$$= \frac{\text{Total force. kg} \times \text{distance moved in m/min}}{4560}$$

$$= \frac{455.2 \times 30}{4560 \times 100} \times 2 \times 50 = 2.99$$

8.3.3 Common Troubles of Reciprocating Pumps and their Remedies

The common troubles of reciprocating pumps, especially the deep well plunger pumps, are summarised in Table 8.4. The suggested remedies are indicated against each.

TABLE 8.4 Common Troubles in the Operation of Reciprocating Pumps and their Remedies

Trouble	Cause	Remedy
Pump does not lift water	Well water below suction limits, leather washer worn	Lower pump body within suction limits, replace washer
Water runs down piping	Valves clogged or defective	Remove valves, clean seats
Pump discharges air bubbles with water	Suction pipe leaking and air sucked through the opening	Remove leakage perfectly, replace pipe pieces if necessary
Water escapes through hole over upper cylinder	Upper cylinder hard and worn out	Replace damaged section
Pump runs too light and no discharge of water	Rod joint disconnected	Open pipe system, make joints tight
Unusual obstruction during the upstroke of the handle	Rod joints loosened and, consequently, overall length increased	Open piping system, tighten rod joints firmly

Adapted from: Kirloskar Bros. Ltd., Satara.

8.3.4 Selection, Installation and Maintenance of Hand Pumps for Domestic Water Supply

Properly installed hand pumps serve as a means of providing clean drinkable water in rural areas. Hand pumps are important in villages which are not provided with piped water supplies. The practice of drawing water from exposed open wells with a rope and bucket, coupled with the practice of bathing and washing near wells and in ponds used for drinking water supplies, are major health hazards in rural areas of developing countries. Most governments have launched large programmes to provide potable water through hand pumps and piped water supplies.

Selection of Hand Pumps

The type of hand pump to be selected will depend on the depth to ground water, the yield of the well, constructional features and efficiency of the pump, and availability of facilities for maintenance and repair. Many of the hand pumps installed earlier went out of use due to the large number of moving parts in them and inadequate repair facilities. Hand pumps working on collars and supports with many moving parts are most liable to go out of order.

The number of hand pumps to be provided in a village depend on the population to be served and the availability of ground water. Since the requirement of domestic water is small compared to that of irrigation, it may often be possible to locate adequate water sources in most areas. Arid regions and hard rock areas with deficient recharge may pose special problems. The criteria for the design of wells, including their spacing, described in the earlier chapters, are adhered to while constructing wells for domestic water supply.

The per capita provision of drinking water under government-sponsored domestic water supply projects, in most states in India, vary from 25 to 70 l/day/person. The discharge of hand pumps varies from 500 to 1500 l/h, depending mainly on the depth to ground water. The number of effective hours of operation of a pump rarely exceeds 6, since a sizable section of the women in rural areas are engaged in farm work and prefer to do domestic work only during specific hours. Thus, the total discharge, in a day of 6 hours, from a hand pump with a capacity of 1000 l/h, may be estimated as 6000 l. With a provision of 40 l of water per day per person, this pump would serve a population of 150 people.

Hand Pump Installation

Hand pumps may be installed in bore wells (Fig. 8.39), filter points (Fig. 8.40) or open wells (Fig. 8.31). If the pumping water level is within 6 m during the dry season, it is advantageous to install a shallow well lift pump, with the pump chamber located at the ground surface on top of the well. A deep well lift pump, with its cylinder submerged in water, is selected when the ground water level is below 6 m (Fig. 8.41). While installing a hand pump in an open well, it is essential to close the top of the well with a removable slab made of reinforced concrete. Well covers made of wooden boards or stone slabs are also used where an RCC slab is considered expensive. The cover should slope towards the periphery of the well in order to drain away the waste water. The well cover will prevent the entry of pollutants from the ground surface into the well.

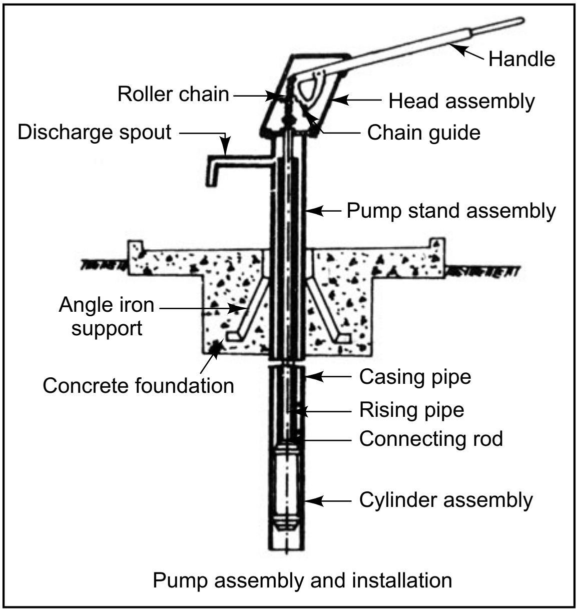


Fig. 8.39 Details of construction, installation and sectional view of an India Mark II deep well pump assembly

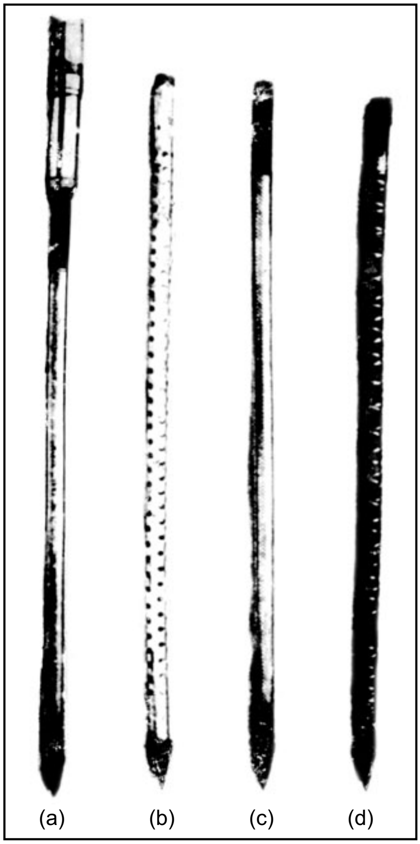


Fig. 8.40 Different types of filter points in tube well-cum-hand pump assemblies: (a) Filter point fixed to the pump body, (b) Perforated pipe base of filter point, (c) Filter with copper sieve envelop, and (d) Filter with nylon netting

Whenever a hand pump is installed in a bore well or filter point, it is essential to provide a permanent platform, about 1 m square, around the well. The platform may be of reinforced concrete or masonry. Brick or stone masonry may be used, depending on their relative costs. Provision of suitable drainage through a pipe or lined channel of semi-circular or rectangular cross-section, is essential in a hand pump installation. The drain should lead the waste water to a natural channel or ditch.

Maintenance and Repair of Hand Pumps

A large number of hand pumps remain out of order due to inadequate arrangements for repair and maintenance. Involvement of the local people in a state sponsored rural water-supply scheme is desirable for the proper maintenance of hand pumps. The responsibility for maintenance and protection could be assigned to people's representatives, headmasters of local schools, or other persons considered suitable. There is a need for training village youth, including artisans, in the repair of hand pumps. An adequate stock of parts exposed to wear and tear should be maintained within easy reach of a group of hand pumps. The parts of hand pumps most exposed to wear and tear are the cup-leather washers of the plunger, valve seats, gaskets, bolts and nuts, cotter pins and sockets. A stock of a few sections of the pump rod, and arrangements for threading the rods are also essential.

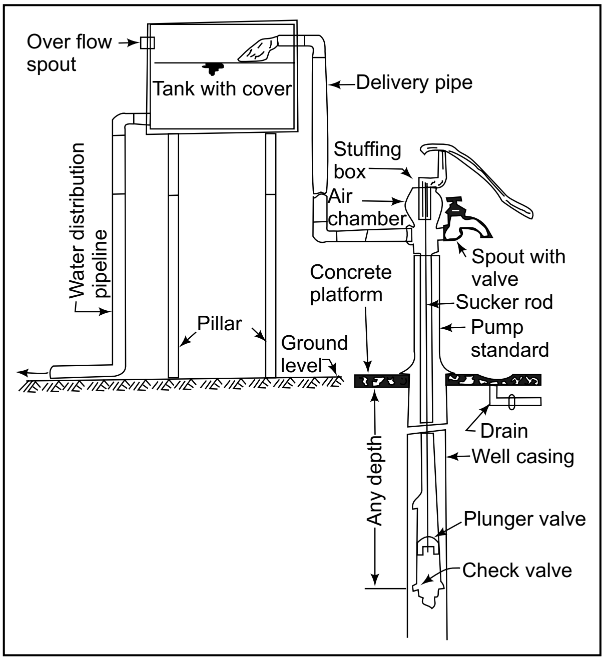


Fig. 8.41 A single-acting deep well force pump installed in a shallow tube well to lift water to an overhead tank for drinking water supply

8.3.5 Rotary Pumps

A rotary pump is a positive displacement pump with a circular motion. It has one or more rotating elements that revolve continuously within a fixed casing. It has no valves and the liquid flows through the passages in a continuous stream.

The designs commonly encountered are those using gears, cams, or vanes (Figs. 8.42 and 8.43). Figure 8.42 illustrates the construction details of a gear rotary pump. The pump body is a plain housing with inlet and outlet pipes and openings for shafts which carry the gears, cams or vanes. In the gear pump, one of the gears is the driver, which is rotated by an outside source of power. The other is the 'idler gear' driven by the driver. The two gears are fitted closely in the housing, and mesh with minimum clearance. They rotate in the direction shown, push the water between the teeth as they mesh together, and force it out through the discharge opening. This creates a partial vacuum and brings in a replacement supply of water along the inlet. Such an operation creates an even, continuous flow. As in the case of reciprocating pumps, the amount of water delivered is constant, regardless of the pressure against which the pump operates. However, the power requirement increases with increase in pressure and discharge.

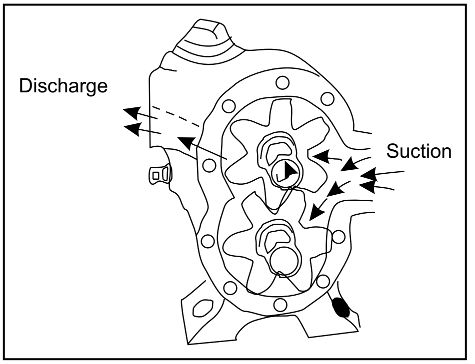


Fig. 8.42 Sketch of spur-gear type rotary pump (open view) showing the principle of working
Adapted from: Goulds Pumps, Inc.

The capacity of the gear pump depends on the speed of operation and the width of the gear teeth or vanes. Rotary pumps are essentially low speed pumps. They could be used to pump water from shallow water bodies requiring a minimum of suction lift. The water should be free of sand and grit, since these materials could cause considerable wear on the loosely fitting gear teeth, vane or cam face. However, due to the necessity for close clearance and metal-to-metal contact, rotary pumps work best and last long when pumping liquids having lubricating qualities. Rotary pumps should not be operated dry. A relief valve should be installed in the discharge line close to the pump to prevent damage to the pump due to the high pressure created by a closed discharge.

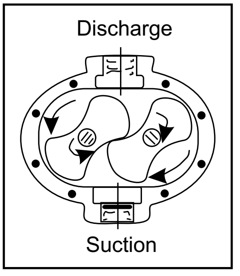


Fig. 8.43 A vane-type rotary pump

8.3.6 Semi-rotary Hand Pumps

Semi-rotary hand operated wing pumps, of double-acting and quadruple-acting types are commonly used for individual water supply systems and in pumping oil and other liquids from tanks and drums. They are often used to lift water from shallow wells or storage tanks at the ground, to overhead tanks.

A double-acting semi-rotary pump consists of a semi-rotating wing cast on the pump spindle. The suction valve box (suction divider) is situated immediately over the suction pipe. Both the wing piston and the suction divider are fitted with hinged flap valves which operate alternatively on either side at each stroke of the pump handle.

Quadruple-acting pumps have higher capacities then double-acting pumps of the same size. The higher capacity is obtained by providing an additional valve box (outlet divider) which retains the liquid in the delivery pipe. In this type of pump, the wing piston is not fitted with flap valves as in the double-acting type, but the liquid is forced alternatively through specially shaped ports.

Installation and Operation

In operating semi-rotary pumps, care should be taken not to take too long a stroke. This may cause the rotar to strike the inlet valve box, which may damage either of these parts. In arranging the suction and delivery pipes, short elbows should be avoided and long sweep bends are to be used. The piping should not be of a size smaller than the bore size of the pump at the suction and delivery ends. Before connecting the suction and delivery piping, the protecting discs between the flanges, provided by the manufacturer, should be removed. It is important that the pump is fixed truly vertical, since an inclination in any direction may impair its efficiency. Foot valves should be provided if the suction lift of semi-rotary pumps exceeds 1.5 m.

8.3.7 Helical Rotor Pumps

The helical rotor or *screw-type* pump is a modification of the rotary-type pump. The main parts of the pump are the polished metal rotor or screw in the form of a helical single-thread worm and the outer helical stator made of rubber (Fig. 8.44). Flexible mountings allow the rotor to rotate eccentrically within the stator. As the rotor is rotated within the stator (at about 1750 rpm), a continuous stream of water is pushed along the cavities in the stator. The rolling action is continuous, resulting in a steady flow of water. The water acts as a lubricant between the two elements of the pump. Helical rotor pumps can be of the shallow well lift type, in which the pump element is located at the ground surface. It may also be of the deep well type, in which the pump element is located down in the well.

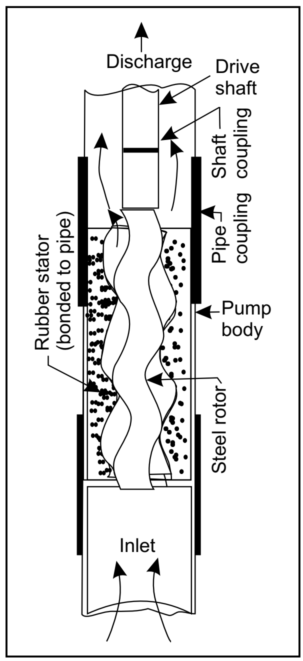


Fig. 8.44 Sectional view of a helical pump

The rotor of a helical pump is usually made of chrome-plated stainless steel, and the stator of cutless rubber. Hence, the pump has a high degree of resistance against wear while pumping gritty materials.

The pump is positive displacement in effect and the horse power required to operate it increases in proportion to the pressure. Hence, it is essential that the pump is not operated under excessive pressure.

Helical rotor pumps may be mounted horizontally (Fig. 8.45) or vertically to a motor. The motor shaft is sealed by a mechanical seal. The pump is self-priming and has a bypass orifice which protects its parts during priming and at times of failure of water supply. The suction pipe is connected to an in-built check valve. Either the starter or rotor is flexibly mounted to allow for eccentric action between them.

8.3.8 Diaphragm Pump

Manually operated diaphragm pumps (Fig. 8.46) are sometimes used for irrigation or drainage pumping. The pump is especially suitable for lifting water containing mud or other impurities. The device consists of a pump chamber enclosed by flat rubber diaphragms on either side. The pedals are fixed to the diaphragms for manual operation. The pump has suction pipe and a discharge outlet at the top

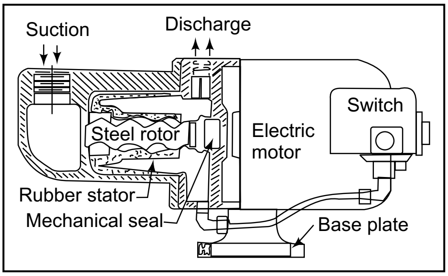


Fig. 8.45 A helical rotor pump coupled to an electric motor

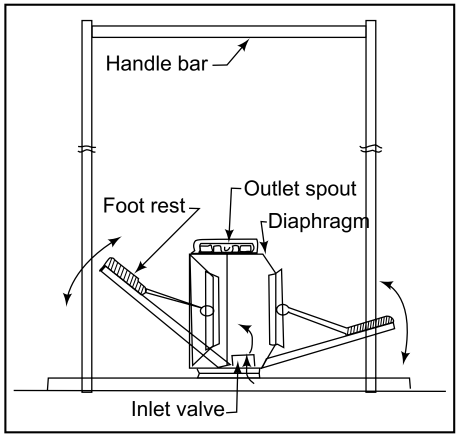


Fig. 8.46 Schematic sketch illustrating the construction and working of a foot-operated diaphragm pump

of its chamber. A stand is provided for the operator to support his hands while operating the pump. The device is operated by a single man standing on the pedals and swinging his body weight to his right and left, thus activating the diaphragm. The movement of the diaphragm on either side of the chamber creates suction on one side, while the other side contributes to the discharge of water. The major feature of diaphragm pumps is that the reciprocating piston has been replaced by a pulsating, flexible membrane. The diaphragm comprises a portion of a chamber past an inlet check valve. Then as the bellows are contracted, water is forced through an outlet check valve. This principle, combined with foot-operation (an idea originally used by ancient blacksmiths for venting forges) has been developed into a low cost low-lift pump. The bellows are made of canvas with metal reinforcing inserts and a wooden frame.

The pedal-operated diaphragm pump is simple in construction, with very few moving parts. However, it is a low-head pump with low discharge capacity. The disadvantage of the diaphragm pump is that its service life can be imporved only by limiting the deflection of the rubber diaphragm. This will result in reducing the capacity of the pump. Hence, diaphragm pumps are rarely used in irrigation. Its main advantage is that it is less likely to wear out since all the working parts, with the exception of the valves, are isolated from contact with the abrading slurries. Hence, it has the ability to pump mud, slurry and corrosive chemicals. Its main use in agriculture is dewatering paddy fields, as it is capable of pumping mud. When used in dewatering flooded fields, its discharge capacity varies from 4,000 to 7,000 litres of water per hour, against heads ranging from 1 to 2 m. Mechanically operated diaphragm pumps are often used in building construction works.

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PROBLEMS

8.1 A 15 litres capacity water bucket is operated by a counterpoise arrangement. The weight of the empty bucket is 1.5 kg. The length of the weight arm of the counterpoise lever is 2.5 m and that of the force arm is 4 m. Determine the weight of the load required to balance the weight of the full bucket.

Ans. 26.4 kg

8.2 A deep well single acting piston pump has a cylinder diameter of 10 cm and stroke of 22.5 cm. The pump makes 300 strokes per minute. Calculate the discharge of the pump in litres per hour. If the total head is 36 m and the pump efficiency is 60 per cent, determine the horse power required to drive the pump.

Ans. 15900 l/hr, 3.5 hp

8.3 A reciprocating pump has a piston diameter of 25 cm. The diameter of the piston rod is 7.5 cm. The piston stroke is 50 cm. The pump is applied to lift water from a depth of 5 m and force it to a height of 20 m. Determine the force required to raise and lower the piston. Estimate the volume of water delivered during the up and down strokes of the piston.
(*Hint*: The force required to raise the piston is the sum of the forces required to produce the suction and the lift, since both these functions take place simultaneously. During the down stroke, the amount of water lifted is equal to the stroke volume of the piston rod).
Ans. 1110 kg, 88.6 kg, 22.28 l/s, 2.215 l/s

SHORT QUESTIONS

I. State True (T) or False (F).

1. From purely economic standpoints, manually operated water lifts are the cheapest.
2. All indigenous water lifts are animal driven.
3. Swing basket is suitable when the height of lift is within the range of 5 m.
4. Swing basket is also called bucket scoop.
5. A *don* is a low head water lifting device.
6. Archimedian screw is the most efficient amongst the manually operated water lifts.
7. Generally, two men are required to operate Archimedian screw.
8. *Picottah*, commonly used in south India, is an adoption of the conventional counterpoise lift.
9. An Archimedian screw is a high head water lifting device.
10. For higher lifts, two or more of counterpoise bucket may be used in series.
11. Chain pump can be operated with a windmill.
12. Manual water lifting from deep wells is limited to irrigation water supply.
13. Water wheel is an animal-driven water lifting device.
14. Animal-driven chain pump and Persian wheel uses same driving mechanism.
15. Height of water lift has no effect on the efficiency of Persian wheel.
16. In a chain pump, water is lifted considerably above the ground level.
17. In rope-and-bucket lift, a spout is fixed at the bottom of the bucket.
18. In circular tow-bucket lift, both the buckets are filled and drawn together.
19. High-head animal operated water lifts can draw water from depth greater than 10 m.
20. The volume of water delivered by a positive displacement pump is constant, regardless of the operating head.
21. Positive displacement pumps are of low speed.
22. Positive displacement pumps are popular in irrigation and drainage.
23. A positive displacement pump has high discharge.
24. Rotary pumps are positive displacement pumps.
25. Lift pumps are designed to pump water to a higher elevation than the pump body.
26. Theoretically, the pump can lift water from a height upto 10.33 m.
27. Manually operated lift pumps are suitable only for lifts upto about 35 m.
28. In single-acting reciprocating pump water is delivered in every stroke.
29. Twin treadle pump is a reciprocating pump.
30. The animal-operated reciprocating pump and Persian wheel have identical mechanism to transport the power of the draft animals to operate the pump.

31. In reciprocating pump the force required to lift the piston is dependent of the diameters of suction and delivery pipes.
32. Hand pump is an example of positive displacement pump.
33. In rotary pump, the liquid flows through the passages in a continuous stream.
34. Diaphragm pumps are not suitable for lifting water containing mud.
35. Rotary pumps works best when pumping liquid having lubricating properties.

Ans. True: 4, 5, 6, 8, 10, 11, 13, 14, 17, 19, 20, 21, 24, 26, 27, 28, 29, 30, 32, 33, 35.

II. Select the correct answer.

1. The cost of lifting a unit quantity of water to a unit height is the lowest in case of
   (a) manually operated water lifts (b) animal operated water lifts
   (c) engine operated pumps (d) electric motor operated pumps
2. By creating a vacuum in a chamber, water can be lifted upto a pressure head of approximately
   (a) 5 m (b) 10 m
   (c) 15 m (d) 20 m
3. The human work capability is about
   (a) 250 watt-hrs per day (b) 500 watt-hrs per day
   (c) 750 watt-hrs per day (d) 1 kilowatt-hr per day
4. Water snail is an example of
   (a) swing basket (b) oscillating trough
   (c) water wheel (d) Archedmedian screw
5. Chain pump works on a similar principal to the
   (a) Archemedian screw (b) water ladder
   (c) oscillating trough (d) Persian wheel
6. To obtain a high efficiency from Archemedian screw, its bottom end should be submerged into water by
   (a) one-quarter (b) half
   (c) three-quarter (d) full
7. Persian wheel is a
   (a) low head water lifting device (b) medium head water lifting device
   (c) high head water lifting device (d) manually operated water lifting device
8. *Picottah* is an adoption of
   (a) swing basket (b) persian wheel
   (c) counterpoise bucket (d) Archemedian screw
9. The most popular indigenous water lift for medium head operation is
   (a) Persian wheel (b) Archemedian screw
   (c) water wheels (d) rope-and-bucket lift
10. In self-emptying bucket lift, a toggle is used to disengage
    (a) rope from the yoke (b) bucket from the rope
    (c) bullock from the yoke (d) pulley from wooden post
11. When the head against which a positive displacement pump operate is changed, the volume of water displaced by it
    (a) remains constant (b) varies directly as the head
    (c) varies as the square of the head (d) varies as cube of the head

12. In reciprocating pumps, the difference between the swept volume and output per stroke is called
    (a) coefficient of discharge (b) volumetric efficiency
    (c) slippage (d) discharge per stroke
13. Manually operated deep well reciprocating pumps are suitable only for lift upto about
    (a) 25 m (b) 30 m
    (c) 35 m (d) 40 m
14. Rotary pump is a
    (a) positive displacement pump (b) centrifugal pump
    (c) rotodynamic pump (d) impulse pump
15. Function of air vessel fitted to delivery side of a single-acting pump is to
    (a) provide variable discharge
    (b) provide steady discharge
    (c) provide intermittent discharge
    (d) provide constant speed

Ans. 1 (d) 2 (b) 3 (a) 4 (d) 5 (b) 6 (b) 7 (b) 8 (c)
9 (a) 10 (a) 11 (a) 12 (c) 13 (c) 14 (a) 15 (b)

9

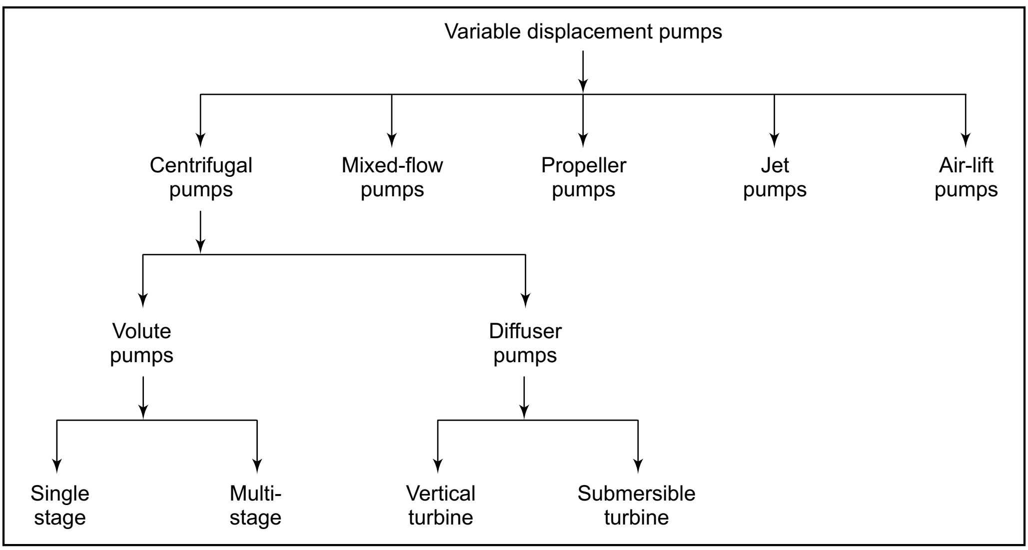
Variable Displacement Pumps and Accessories

The distinguishing feature of variable displacement pumps is the inverse relationship between the discharge rate and the pressure head. As the pumping head increases, the discharge rate decreases. Unlike positive displacement pumps, variable displacement pumps require the greatest input of power at low heads because of increase in discharge as the pumping head is reduced.

Variable displacement pumps of the impeller type, including centrifugal, mixed-flow and propeller pumps, are predominantly used in irrigation and drainage pumping. They are also common in drinking water supply systems operated by electric motors or engines. They use a rotating impeller to pump water. They are available for use under widely varying operating conditions, including low to high discharge and operating heads.

9.1 CLASSIFICATION OF VARIABLE DISPLACEMENT PUMPS

The broad classification of the commonly used variable displacement pumps is shown in the following chart:



9.2 CENTRIFUGAL PUMPS

Centrifugal pumps are used to pump water from reservoirs, lakes, stream and shallow wells. They are also used as booster pumps in irrigation pipelines.

9.2.1 Principles of Operation

A centrifugal pump may be defined as one in which an impeller rotating inside a close-fitting case draws in the liquid at the centre and, by virtue of centrifugal force, throws out through an opening or openings at the side of the casing. The underlying hydraulic principle is the production of high velocity and the partial transformation of this velocity into pressure head. In operation, the pump is filled with water and the impeller rotated. The blades cause the liquid to rotate with the impeller and, in turn impart a high velocity to the water particles. The centrifugal force causes the water particles to be thrown from the impeller into the casing. The forward flow through the impeller reduces pressure at the inlet, allowing more water to be drawn in through the suction pipe by atmospheric pressure or an external pressure. The liquid passes into the casing, where its high velocity is reduced and converted into pressure and the water is pumped out through the discharge pipe. This conversion of velocity energy into pressure energy is accomplished either in a volute casing or in a diffuser.

The principle of operation of a centrifugal pump can be explained through the example of swinging a pail (Fig. 9.1). When a pail filled with water is swung in a circle, in a vertical or horizontal plane, the water stays in the pail because of the centrifugal force. This makes the pail seem very heavy. If the pail has a hole in it, the water would spurt out with considerable force. If it were possible to connect this hole to a hose and to elevate the hose vertically, several meters in the air, water in the pail would be discharged through the hose.

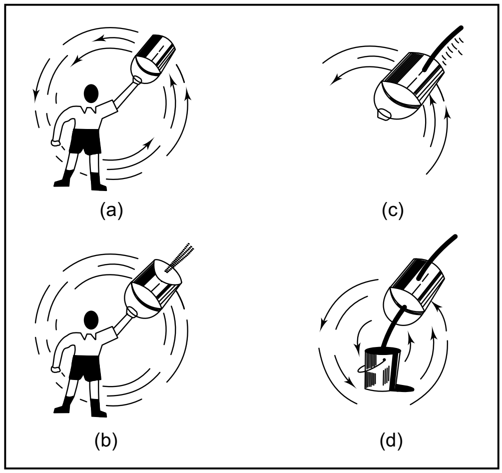


Fig. 9.1 Elementary principle of the centrifugal pump
Courtesy: Kelly and Lewis (1962)

In the next step, suppose a cover is put on the pail and a hose is connected with the cover on one side and a pail of water on the ground on the other. A centrifugal pump, in principle, would be developed. The centrifugal force of the water in the rotating pail will force the water out of the discharge hose, thus creating a partial vacuum in the rotating pail. This vacuum will cause a transfer of water from the stationary pail to the rotating pail. This is because atmospheric pressure on the surface of the water in the stationary pail forces the water into the vacuum of the rotating pail. Theoretically, such a system would continue to operate, provided no air enters with the water from the stationary pail.

The swinging pail is readily duplicated in a practical construction in which a set of rotating blades, or vanes, commonly called an impeller, is used. The impeller vanes act as the arm and pail. They ‘sling’ the liquid and impart centrifugal force and velocity. The impeller is arranged to rotate inside a casing which gathers the liquid from the suction entrance and directs it to the discharge opening.

Parts of a Centrifugal Pump

A centrifugal pump is a rotary machine consisting of two basic parts–the rotary element or impeller and the stationary element or casing (Fig. 9.2). The impeller is a wheel or disc mounted on a shaft and provided with a number of vanes or blades which are usually curved. The vanes are arranged in a circular array around an inlet opening at the centre. In some pumps, a diffuser consisting of a series of guide vanes of blades surrounds the impeller (Fig. 9.3). The impeller is secured on a shaft mounted on suitable bearings. The shaft usually has a stuffing box or a seal, where it passes through the casing wall (Fig. 9.4). The stuffing-box packing are generally made of asbestos or organic fibre. The casing surrounds the impeller and is usually in the form of a spiral or volute curve with a cross-sectional area increasing towards the discharge opening.

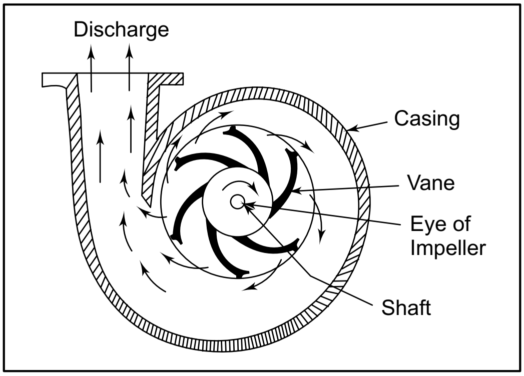


Fig. 9.2 Volute type centrifugal pump

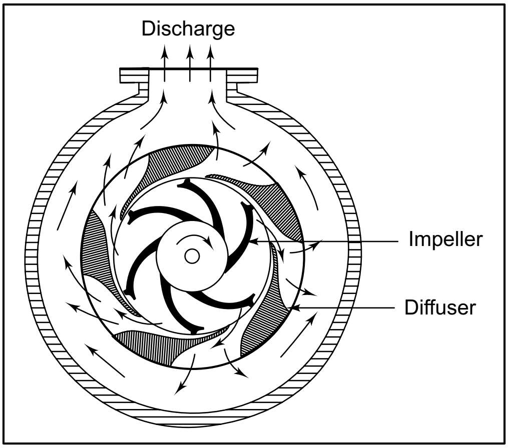


Fig. 9.3 Diffuser type centrifugal pump

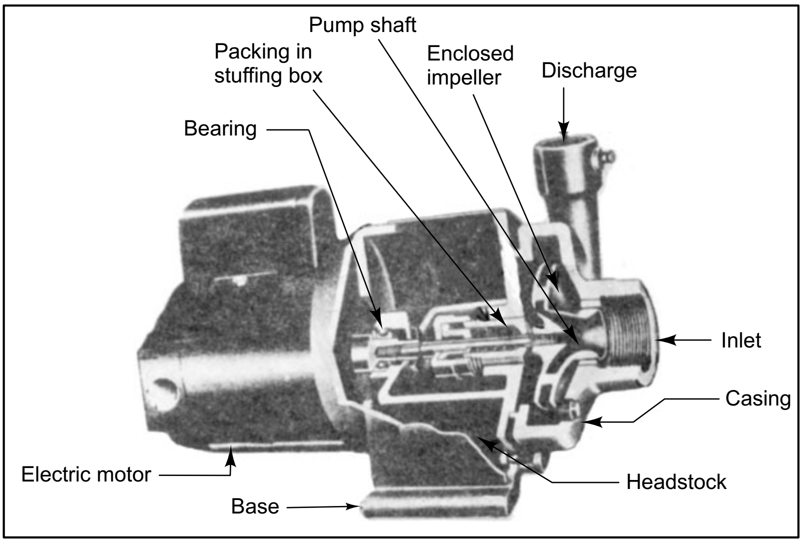


Fig. 9.4 Cut-away section of a horizontal centrifugal pump coupled to electric motor as a single unit

By changing the shape of the vanes, different characteristics are obtained. By enlarging the diameter of the inlet eye and the width of the impeller, the quantity of water that a pump can deliver against a given head is increased.

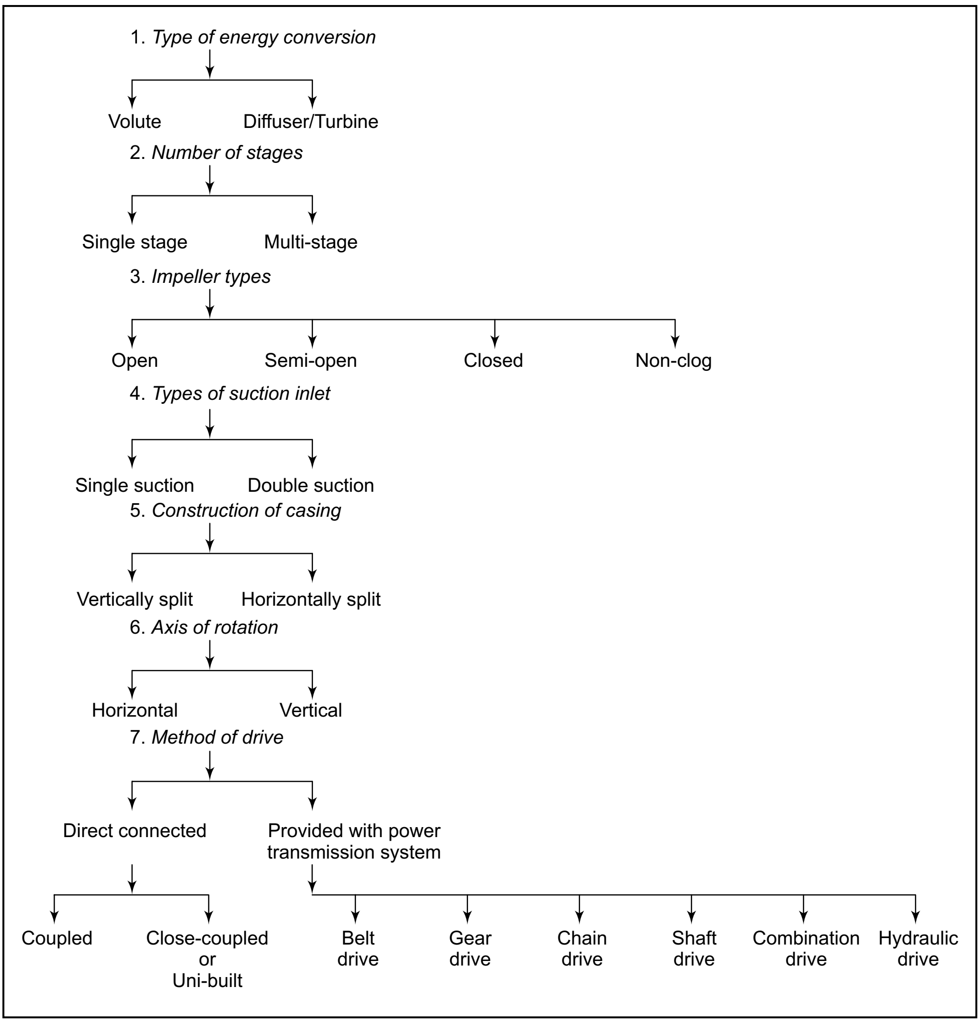
The leakage of water past an impeller, from the high pressure delivery side to the low pressure inlet area, results in considerable loss of energy. Hence, a sealing ring is provided between the impeller and the pump casing. The sealing ring may be a simple ring of close clearance or an elaborate labyrinth ring.

A bed plate is provided at the base of the pump body for mounting the pump and the driving motor or engine, thus providing a foundation on which they can be installed as a unit.

9.2.2 Classification

Centrifugal pumps are built in a wide variety of types. They may be classified into the following, on the basis of the type of energy conversion, constructional features, axis of rotation and method of drive.

Classification of Centrifugal Pumps



Volute Centrifugal Pumps

Most of the irrigation pumps used in India and other developing countries are of the volute type. The volute pump (Fig. 9.2) has a casing made in the form of a spiral or volute curve. The volute casing starts with a small cross-sectional area near the impeller periphery, which increases gradually towards the pump outlet. The casing is proportioned to reduce gradually the velocity of water, as it flows from the centre of the impeller to the discharge end, thus changing the velocity head into the pressure head to lift water to the required height.

Diffuser or Turbine Pumps

In a turbine-type pump, the impeller is surrounded by diffuser vanes (Fig. 9.3). The diffuser vanes, like the impeller vanes, are curved and gradually enlarge to the outer end where the liquid enters the pump casing. In a diffuser pump, a major part of the conversion of velocity energy into pressure energy takes place between the diffuser vanes. The diffuser vane casing was introduced in the design of pumps adopting the water-turbine practice, where the diffusion vanes are indispensable. Hence, these pumps are often called turbine pumps.

The choice between volute-type and turbine-type pumps varies with the conditions of use. Ordinarily, the volute-type pump is preferred for medium and large capacity and medium and moderately high head applications. Turbine pumps are usually used for high head conditions. Similarly, turbine pumps are most suitable in deep tube wells because of their design advantage where the diameter of the pump is small.

Single-Stage and Multi-Stage Pumps

A single-stage pump is one in which the total head is developed by a single impeller. A multi-stage pump has two or more impellers on a common shaft, acting in series in a single casing (Fig. 9.5). The liquid is conducted from the discharge of the preceding impeller, or stage, to the inlet of the following

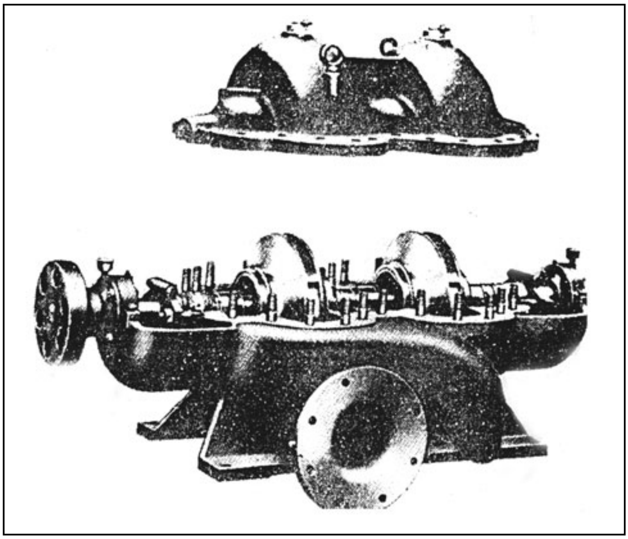


Fig. 9.5 A two-stage horizontal centrifugal pump with top cover lifted up
Courtesy: Lee Howl & Co. Ltd., London

impeller, causing an increase in the pressure head as it passes through each stage. The use of multi-stage pumps is a standard practice in volute as well as turbine type pumps for operation under high heads.

For a given type of impeller, the characteristics exhibited by a multi-stage pump are as follows:

1. The head and power requirements increase in direct proportion to the number of stages (impellers).
2. The discharge capacity and efficiency are almost the same as for a single stage of the pump operating alone.

Types of Impellers

The design of the impeller greatly influences the efficiency and operating characteristics of centrifugal pumps. Centrifugal pump impellers used in irrigation practice may be open, semi-open or close (Fig. 9.6). An *open impeller* consists essentially of a series of vanes attached to a central hub. It is used to pump water having considerable amounts of small solids. There is a minor reduction in efficiency

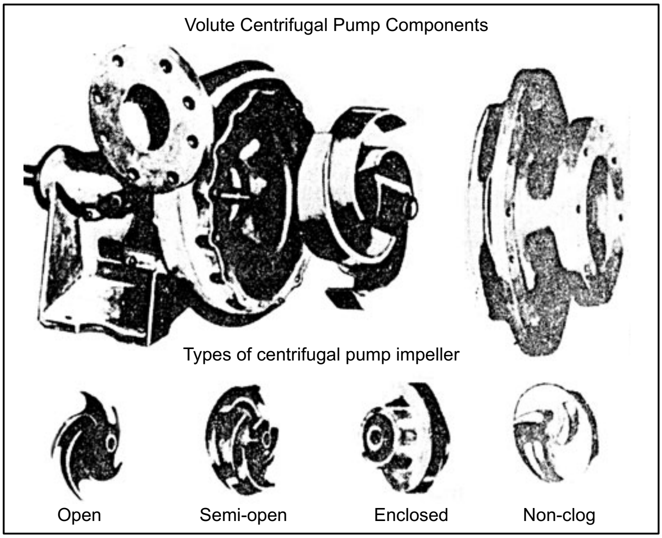


Fig. 9.6 Top: An exploded view of a volute-type horizontal centrifugal pump
Bottom*:* Types of impellers used in centrifugal pumps
Adapted from: Goulds Pumps Inc. (Olmstead, 1965)

when open-type impellers are used. A *semi-open* (or semi-enclosed) impeller has a shroud or side wall at the back. It can be used to pump water having some amount of suspended sediments. It is more efficient than open impellers. In an *enclosed impeller*, the vanes are enclosed between shrouds or side walls on either side. It is designed to pump clear water. Enclosed impellers develop somewhat higher efficiencies, especially in high pressure pumps. They are most efficient amongst the three types of impellers.

For pumping ordinary water, centrifugal pump impellers may be made of bronze or cast iron. To handle brackish or salt water, gun metal impellers are commonly used. Impellers for light duty could be made of rigid plastic materials.

Non-Clog Impeller Pumps

Non-clog pumps (Fig. 9.7), are specially designed for sewage service. They have vanes which are well rounded at their entrance ends and have large passage-ways between the vanes. They can handle sewage water containing solid particles, rags and other impurities.

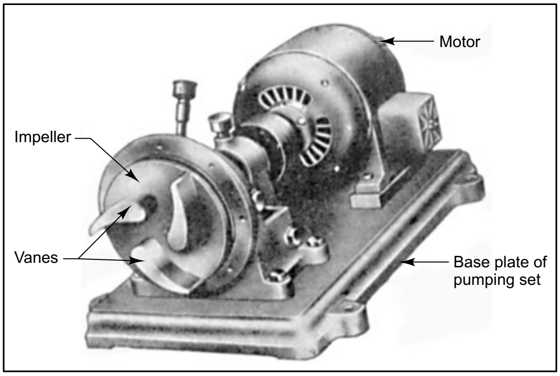


Fig. 9.7 Exposed view of a non-clog volute centrifugal pump coupled to an electric motor
Courtesy: Albany Engg. Co. Ltd.

Single-Suction and Double-Suction Pumps

In a single-suction pump, the liquid enters the impeller from one side only. In a double-suction pump, it enters from both sides. A double-suction impeller is similar to two single-suction impellers cast back to back. It is, theoretically, in axial hydraulic balance, making a thrust bearing unnecessary. However, due to manufacturing difficulties, double-suction pumps are not as common as single-suction pumps.

Horizontal-Split and Vertical-Split Casing Pumps

According to construction of the casing of a centrifugal pump, they are classified as horizontal-split casing (Fig. 9.4) or vertical-split casing (Fig. 9.8) pumps.

Horizontal Centrifugal Pumps

A horizontal centrifugal pump has a vertical impeller mounted on a horizontal shaft (Fig. 9.5). This type of pump is most commonly used in irrigation. It costs less, is easier to install and more accessible for inspection and maintenance. Its main limitation is that the pump is located above the water surface and the suction lift is limited to about 6.5 m.

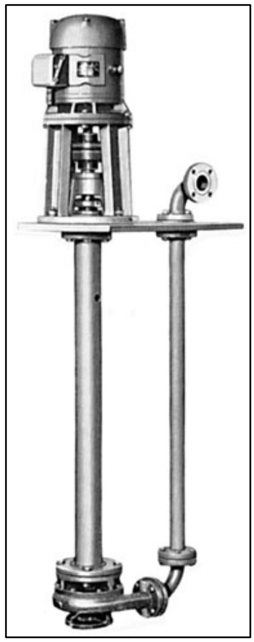


Fig. 9.8 A vertical submersible type volute centrifugal pump driven by a Vertical drive electric motor
Courtesy: Lee Howl & Co. Ltd., London

Vertical Centrifugal Pumps

A vertical centrifugal pump has a horizontal impeller mounted on a vertical shaft. This type of pump has the advantage that it can be lowered into the well, thus overcoming the problem of limited suction lift, as in the case of a horizontal centrifugal pump. Further, the vertical shaft is extended to the top of the well where the power unit is located. Volute-type vertical centrifugal pumps may be either submerged or exposed. The body of an exposed pump is usually set in a sump, at a level that will accommodate the suction lift.

In a submerged pump, the impeller and suction entrance remain submerged below the water level. Thus, the pump does not require priming. However, this arrangement is not popular in irrigation practice due to the difficulty in lubricating the bearings. Volute-type vertical centrifugal pumps are usually limited to pumping from sumps or pits. Hence, they are often referred to as sump pumps.

Close-Coupled Monoblock Pumps

Close-coupled pumps (Fig. 9.9(a) and (b)) often called monoblock pumps, are built with a common shaft and bearing for the pump and prime-mover, so as to form a single compact unit (Fig. 9.10). They are commonly used with electric motor driven pumping sets of small to medium capacity. They have the advantage of a slightly higher efficiency due to the elimination of transmission losses and compactness. The major problem is the difficulty in removing the electric motor for repair. Hence, monoblock pumps are generally limited to small-size, usually 1 to 5 hp units.

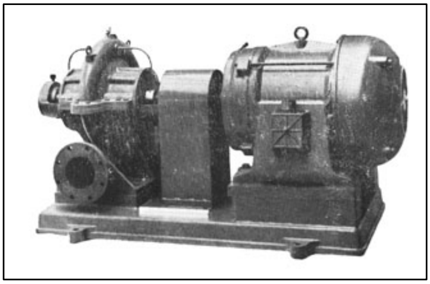


Fig. 9.9(a) A horizontally split volute centrifugal pump coupled to an electric motor. Note the protective shield over the couplong *Courtesy:* Albani Engg. Co. Ltd.

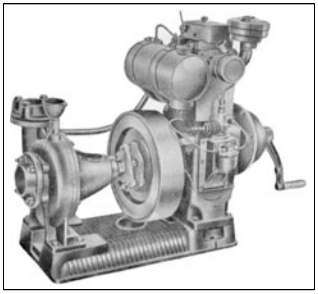


Fig. 9.9(b) A horizontal centrifugal pump coupled to a vertical diesel engine *Courtesy*: Kirloskar Brothers, Ltd. Pune, (Anon., 1962)

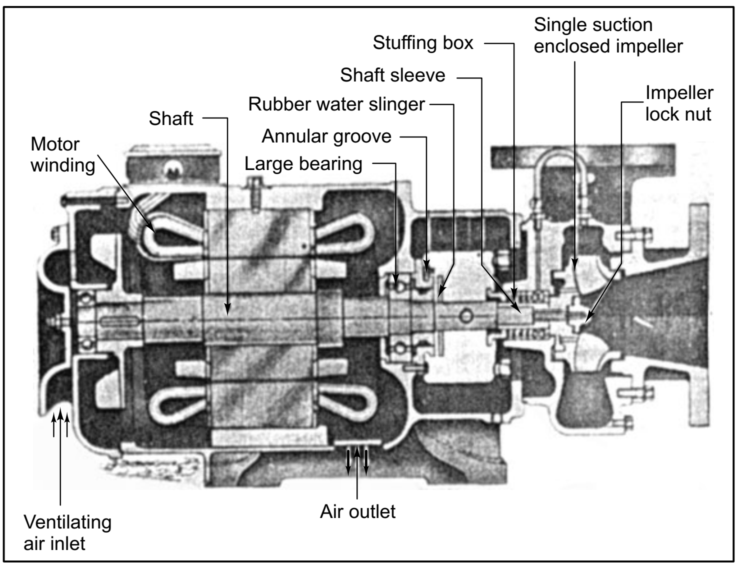


Fig. 9.10 Sectional view of a motor driven monoblock horizontal volute centrifugal pump *Courtesy:* Worthington Simpson Pumps, Best & Co., Chennai

Pumps with Flexible Coupling

In this type, the pump is mounted directly to its driver through a flexible coupling. Flexible couplings are most commonly used to connect the pump shaft to the motor or engine shaft. They permit minor misalignment of the shafts. The removal of the power unit from the pump for repair is easy.

Pumps Connected with Belt, Gear, Shaft or Chain Drives

In many situations, especially in case of engine-driven pumping sets, the pump has to be located close to the water level in a well or stream, but it is not covenient to locate the engine close to it. In such a case, a suitable power transmission system is to be adopted. The power transmission systems commonly used are belt (Fig. 9.11), chain, gears and shaft. Suitable combinations of two or more of the above drives are also sometimes required. Among the various drives, belt drive is the most common. In belt drive, the pump is provided with a pulley head.

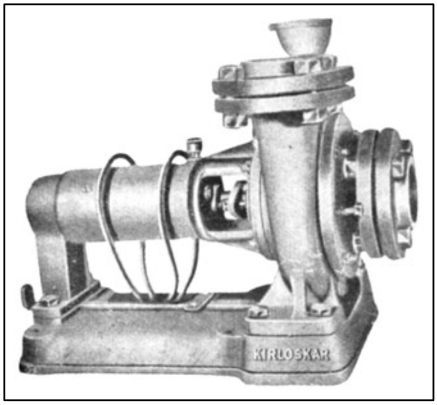


Fig. 9.11 A belt-driven horizontal volute centrifugal pump provided with fast and loose pulleys
Courtesy: Kirloskar Brothers Ltd., Pune (Anon., 1962)

9.3 FRICTION HEAD IN PIPE SYSTEM

The head losses in piping installations include the energy or head required to overcome the resistance of the pipeline and fittings (including strainer, valves, elbows, bends, reducing sockets and tees) in the pumping system. A friction head exists on both the suction and discharge sides of a pump, and varies with the rate of flow of water, pipe size, condition of the interior of the pipe and the material of which the pipe is made.

Loss of Head Due to Friction in a Pipe

Loss of head due to friction in a pipe, between two points at a distance l apart is given by the formula

$$h_f = \frac{4flv^2}{2gd} \tag{9.1}$$

where, f = coefficient of friction for the pipe, fraction
l = length of pipe, m
d = diameter of pipe, m

The friction coefficient f depends upon the smoothness or roughness of the pipe surface. The value of f is less if the pipe is new and smooth. It may be determined by carrying out the actual test, using Eq. (9.1). The value of f is calculated for observed values of h_f, l, v and d. The head loss in galvanized iron pipes and rigid PVC pipes of different sizes, under varying discharge rates, is given in Table 9.1 and 9.2, respectively.

Example 9.1 Compute the head loss due to friction in a pipe 7.5 cm in diameter and 100 m long, when the water is flowing at a velocity of 2 m/s. The value of f may be assumed to be 0.005.

Solution

$$d = 0.075 \text{ m}, \quad l = 100 \text{ m},$$
$$v = 2 \text{ m/s} \quad g = 9.81 \text{ m/s}^2$$

Head loss due to friction, $$h_f = \frac{4flv^2}{2gd}$$

$$= \frac{4 \times 0.005 \times 100 \times 2 \times 2}{2 \times 9.81 \times 0.075} = 5.43 \text{ m}$$

Friction Loss in Pipe Fittings and Pump Accessories

Head losses in the strainer and foot valve of a pump are obtained from the following formulae:

Strainer $$h_f = k_s \frac{v^2}{2g} \tag{9.2}$$

Foot valve $$h_f = k_f \frac{v^2}{2g} \tag{9.3}$$

where, h_f = head loss due to friction, m

k_s and k_f are constants

The value of k_s usually assumed is 0.95, and that of k_f is 0.80.

The head loss in valves and pipe fittings can be determined from the nomographic solution presented in Fig. 9.12. The dotted line in the figure illustrates the use of the nomograph for determining the head loss due to sudden contraction in a pipeline when the ratio between the small diameter d and large diameter D is 1:2 and the value of d is 80 mm. The point 80 mm on the pipe-size scale is joined to the point on the nomograph representing a sudden contraction of $d/D = \frac{1}{2}$. The point of intersection of the line on the equivalent pipe-length scale gives the desired resistance value as equivalent to the friction loss in a 0.9 m long straight pipe of 80 mm size. The actual head loss in an 80 mm diameter pipe at the given discharge rate is obtained from Table 9.1. The same may be computed using Eq. (9.1). It may be noted that, for sudden enlargements or sudden contractions the smaller diameter d is used on the pipe-size scale.

9.4 TOTAL PUMPING HEAD

The total pumping head, often called the total head, is the energy imparted to the water by the pump. The energy in pumping is often expressed in units of length.

Practically, there could be two situations in pumping: (1) The free surface of the source of water supply is below the centre line of the pump, (2) It is above the centre line of the pump (as is the usual case in turbine, submersible, and propeller pumps). Suction lift and suction head exist in the former and latter cases, respectively. The various terms used in designating pressure heads in pumping sets are defined as follows:

TABLE 9.1 Head Loss due to Friction in Galvanized Iron Pipes in Metres per 100 Metres of Pipe Length, m

Discharge	**Pipe diameter, cm**										
***l*/s**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**10.0**	**12.5**	**15.0**	**20.0**	**25.0**	**30.0**
1.0	3.7	1.1	0.43	—	—	—	—	—	—	—	—
1.2	5.0	1.6	0.58	0.27	—	—	—	—	—	—	—
1.4	7.3	2.2	0.83	0.37	—	—	—	—	—	—	—
1.6	9.2	2.8	1.10	0.50	0.23						
1.8	11.8	3.7	1.40	0.62	0.29	—	—	—	—	—	—
2.0	15.5	4.5	1.70	0.73	0.37	—	—	—	—	—	—
2.2	16.2	5.2	2.15	0.90	0.44	—	—	—	—	—	—
2.4	20.5	6.4	2.50	1.07	0.52	0.16	—	—	—	—	—
2.6	23.5	7.5	2.90	1.27	0.62	0.18	—	—	—	—	—
2.8	27.5	8.7	3.30	1.47	0.70	0.22	—	—	—	—	—
3.0	32.0	10.0	3.80	1.68	0.83	0.25	—	—	—	—	—
3.5	42.5	13.5	5.30	2.30	1.10	0.33					
4.0	56.0	17.5	7.30	3.00	1.50	0.45	0.13	—	—	—	—
4.5	71.5	22.5	8.80	3.80	1.85	0.55	0.17	—	—	—	—
5.0	87.0	28.0	10.80	4.70	2.30	0.68	0.22	—	—	—	—
5.5	—	33.0	12.40	5.70	2.70	0.83	0.26	0.095	—	—	—
6.0	—	40.0	15.50	6.80	3.20	0.96	0.32	0.118	—	—	—
6.5	—	47.0	18.30	8.00	3.80	1.15	0.36	0.140	—	—	—
7.0	—	54.0	21.50	9.30	4.50	1.30	0.42	0.17	—	—	—
7.5	—	62.0	24.00	10.60	5.20	1.50	0.47	0.18	—	—	—
8.0	—	70.0	28.00	11.60	6.00	1.80	0.55	0.21	—	—	—
8.5	—	80.0	31.00	13.30	6.80	2.00	0.62	0.23	—	—	—
9.0	—	90.0	36.00	15.00	7.50	2.20	0.68	0.27	—	—	—
9.5	—	100.0	38.00	17.00	8.30	2.50	0.76	0.29	—	—	—
10	—	—	43.00	19.00	9.40	2.80	0.85	0.32	0.065	—	—
12	—	—	63.00	27.00	13.00	4.00	1.23	0.47	0.10	—	—
14	—	—	86.00	37.00	18.00	5.50	1.65	0.63	0.13	—	—
16	—	—	—	47.00	23.00	7.20	2.20	1.05	0.22	0.055	—
18	—	—	—	60.00	30.00	9.00	2.80	1.05	0.22	0.068	—
20	—	—	—	72.00	37.00	11.00	3.30	1.30	0.27	0.080	—
22	—	—	—	86.00	45.00	13.50	4.10	1.60	0.33	0.100	0.038

(*Contd.*)

TABLE 9.1 (*Contd.*)

Discharge					Pipe diameter, cm						
l/s	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**10.0**	**12.5**	**15.0**	**20.0**	**25.0**	**30.0**
24	—	—	—	—	52.00	16.00	4.80	1.90	0.40	0.120	0.045
26	—	—	—	—	62.00	18.70	5.60	2.20	0.47	0.145	0.055
28	—	—	—	—	72.00	22.00	6.60	2.50	0.55	0.165	0.060
30	—	—	—	—	80.00	25.00	7.50	2.80	0.63	0.19	0.070
35	—	—	—	—	—	33.00	10.30	4.40	0.85	0.27	0.095
40		—	—	—	—	45.00	13.50	5.20	1.10	0.33	0.128
45	—	—	—	—	—	56.00	17.00	6.50	1.40	0.43	0.16
50	—	—	—	—	—	70.00	21.00	8.30	1.70	0.55	0.20
55	—	—	—	—	—	85.00	26.50	9.70	2.20	0.65	0.24
60	—	—	—	—	—	100.00	32.00	11.50	2.50	0.75	0.28
65	—	—	—	—	—	—	37.00	14.90	2.90	0.90	0.34
70	—	—	—	—	—	—	42.00	16.30	3.50	1.08	0.40
75	—	—	—	—	—	—	48.00	18.50	3.90	1.20	0.46
80	—	—	—	—	—	—	55.00	22.00	4.30	1.40	0.52
85	—	—	—	—	—	—	60.00	23.00	5.00	1.50	0.58
90	—	—	—	—	—	—	68.00	27.00	5.60	1.70	0.65
95	—	—	—	—	—	—	75.00	30.00	6.30	1.90	0.72
100	—	—	—	—	—	—	85.00	33.00	7.00	2.20	0.80

Adapted from: Kirloskar Brothers Ltd., *Engineering Data* (Anon., 1976)

TABLE 9.2 Friction Head Losses in Metres per 100 Metres Length of PVC Pipeline, at Pressure Rating of 2.5 kg/cm^2

Discharge	Pipe diameter			
l/s	90 mm	110 mm	125 mm	140 mm
2.0	0.13	—	—	—
2.5	0.20	—	—	—
3.0	0.28	—	—	—
3.5	0.37	0.14	—	—
4.0	0.48	0.18	—	—
4.5	0.59	0.23	0.13	—
5.0	0.71	0.27	0.15	—
5.5	0.85	0.33	0.17	—
6.0	0.98	0.38	0.21	0.12
6.5	1.15	0.44	0.24	0.14
7.0	1.32	0.50	0.27	0.16
7.5	1.50	0.57	0.32	0.19
8.0	1.66	0.63	0.35	0.21
8.5	1.86	0.71	0.39	0.23
9.0	2.04	0.78	0.43	0.26
9.5	2.24	0.87	0.47	0.28
10	2.51	0.95	0.53	0.31
11	2.88	1.12	0.62	0.36
12	3.39	1.29	0.71	0.42
13	3.98	1.48	0.83	0.49
14	4.47	1.70	0.94	0.56
15	5.13	1.95	1.07	0.64
16	5.75	2.19	1.20	0.71
17	6.46	2.40	1.35	0.79
18	7.16	2.72	1.51	0.89
19	7.94	2.95	1.66	0.99
20	8.61	3.27	1.82	1.10
25	—	4.78	2.26	1.60
30	—	6.68	3.67	2.14
35	—	8.91	4.90	2.88
40	—	—	6.17	3.63
45	—	—	7.76	4.32
50	—	—	9.33	5.37
60	—	—	—	7.42
70	—	—	—	9.79

Adapted from: Kirloskar Brothers, Ltd., *Engineering Data* (Anon., 1976)

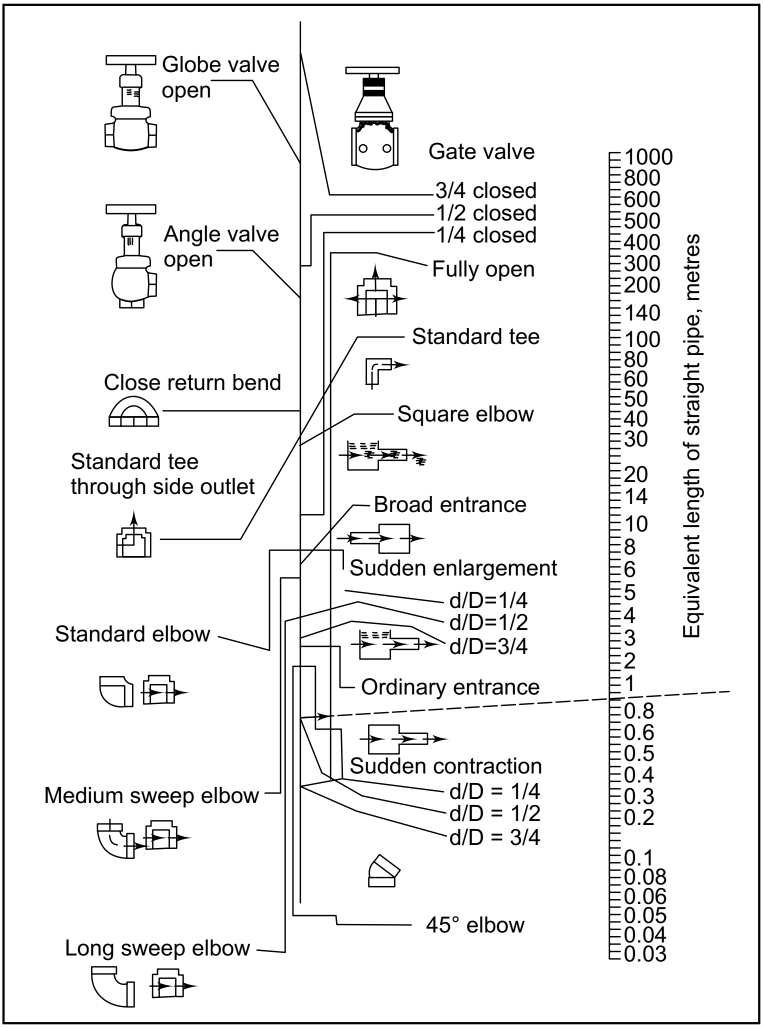


Fig. 9.12 Nomograph for determining friction losses in pipe fittings
Adapted from: Kirloskar Bros. Ltd. *'Engineering Data'* (Anon., 1976)

(i) The Surface of the Source of Water Supply is Located Below the Centre Line of the Pump

Static Suction Lift (h_{ss}): It is the vertical distance from the free suction water level (pumping water level) to the centre line of the pump.

Total Suction Lift (H_s): It is the sum of the static suction lift (h_{ss}) and the losses due to friction in the suction pipe and fittings, including the entrance losses at the inlet to the suction pipe (h_{fs}).

$$\therefore \qquad H_s = h_{ss} + h_{fs} \qquad (9.4)$$

Static Delivery Head (h_d): The static delivery head, also called the static delivery lift, is the vertical distance between the centre line of the pump and the point of free discharge or the level of the free surface of the discharge liquid.

Delivery Head (H_d): It is the sum of the static delivery head and friction losses in the delivery pipe (h_{fd}).

$$H_d = h_d + h_{fd} \tag{9.5}$$

As measured on a test bench, the delivery head is the sum of the pressure gauge reading at the discharge end of the pump and the distance between the centre line of the pump and the gauge. The distance between the centre line of the pump and the gauge will be positive if the gauge is above the pump, and vice versa.

Velocity Head (H_v): This is the pressure required to create the velocity of flow in the pipe.
Expressed mathematically,

$$H_v = \frac{v^2}{2g} \tag{9.6}$$

where, H_v = velocity head, m
g = acceleration due to gravity, m/s^2 (usual value 9.81 m/s^2)

Total Head (H): It is the sum of the total suction head, delivery head and velocity head.

$$\therefore \quad H = H_d + H_s + \left(\frac{V_d^2}{2g} + \frac{V_s^2}{2g}\right) \tag{9.7}$$

$V_d^2/2g$ and $V_s^2/2g$ are the velocity heads on the delivery side and the suction side, respectively.

(ii) The Source of Water Supply is above the Centre Line of the Pump

Static Suction Head (h_s): It is the difference in elevation between the centre line of the pump and the level of water at the source of pumping.

Total Suction Head (H_{ts}): It is given by the static suction head (h_s) minus all the friction losses in the pipe and fittings and entrance losses in the suction pipe.

$$\therefore \quad H_{ts} = h_s - h_{fs} \tag{9.8}$$

As determined in a pump test, the total suction head is the reading of the pressure gauge connected to the pump suction, expressed in metres of water and corrected to the pump centre line, plus the velocity heads at the points of gauge attachment.

The static delivery lift or head (h_d) and the delivery head (H_d) have already been defined.

Total Head (H): It is defined as the sum of the delivery head and velocity head minus the total suction head.

Expressed mathematically,

$$H = H_d + \frac{V_d^2}{2g} - H_{ts} - \frac{V_s^2}{2g} \tag{9.9}$$

If the delivery and suction pipes are of the same diameter, total head,

$$H = H_d - H_{ts}$$

9.5 CAVITATION

While pumping water, if the pressure at any point inside a pump drops below the vapour pressure, corresponding to the temperature of the liquid, the liquid will vaporise and form cavities of vapour. The bubbles of vapour are carried along with the stream until a region of higher pressure is reached, when they collapse or explode with tremendous shock on adjacent walls. This phenomenon is called cavitation.

The sudden in-rush of liquid into the cavity created by the collapsed vapour bubbles causes mechanical destruction or 'erosion'. Apart from this, corrosion also occurs due to chemical reaction between the gases and metal, and additional destruction of the metal takes place. There is an accompanying noise, varying from a low rumbling to loud knocks, and a resultant heavy vibration of the pumping unit. The energy required to accelerate the flow of water to fill the hollow spaces results in loss of power. Thus, cavitation is accompanied by a reduction in efficiency of the pump.

Cavitation will take place primarily at the vane inlet portion of the impeller, on the vanes and the shrouds. At the point of lowest pressure, gas pockets are formed and, further upstream, at the point where the explosion takes place, erosion and wear due to cavitation will occur. Thus, cavitation interferes with pumping. It may also damage the pump parts by pitting and/or excessive vibration.

Cavitation is quantified through the cavitation coefficient σ. It can be defined as

$$\sigma = \frac{H_{sv}}{H} \tag{9.10}$$

where, H_{sv} = net positive suction head at the critical point, m
H = total head, m

The critical value of σ, at which cavitation will begin, can be determined by testing the pump at constant speed and capacity and varying the suction lift.

The relationship between the cavitation parameter σ and the percentage drop in the efficiency of selected pumps tested is given in Fig. 9.13. It may be observed from Fig. 9.13 that the percentage drop in efficiency increases with decrease in the value of σ. There is a slight variation in percentage drop in efficiency at higher σ values. The drop in efficiency changes rapidly when the value of σ is reduced below a critical limit.

The maintenance of a σ value greater than 0.3 results in the successful operation of the centrifugal pump. This critical limit of σ refers to a safe suction lift, which is nearly 4.5 to 5 m for most pumps.

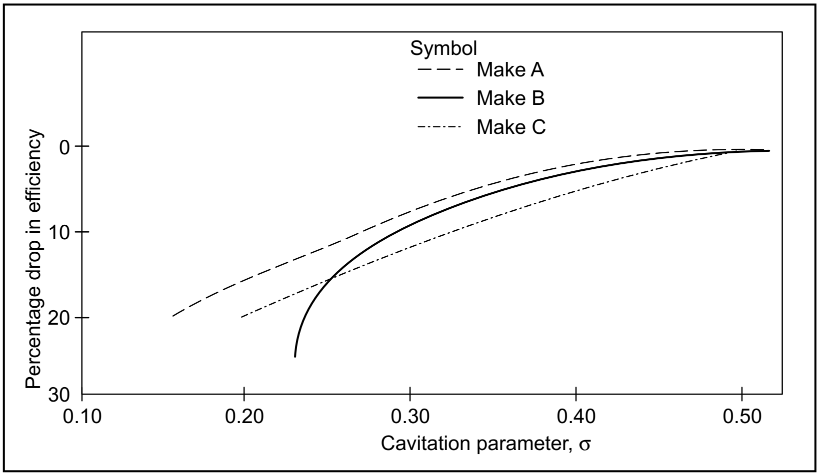


Fig. 9.13 Relationship between cavitation parameter σ and drop in efficiency of pumps

9.5.1 Net Positive Suction Head (NPSH)

Cavitation occurs when the hydraulic head at the pump inlet is too low for its operation. When the water enters the pumps, the head must be high enough. As the velocity of flow increases, the pressure is decreased within the pump. The pressure, however, should not drop to the vapour pressure of water at any place in the flow path. The pressure head needed at the pump inlet may be termed the net positive suction head or net required inlet head. The total net positive head will be the sum of the net positive suction head plus entrance and other friction losses in the suction piping.

The suction head required in a pump may be less than or greater than the atmospheric pressure. When the pumping water level is below the pump inlet, the total net positive suction head is equal to the atmospheric pressure (expressed in metres) minus the vertical distance from the pumping water level to the pump inlet. If the pumping water level is above the pump inlet, the net positive suction head is atmospheric pressure plus the vertical distance from the pumping water level to the pump inlet. The difference between the atmospheric pressure and the total net positive suction head provides either the maximum suction lift or the minimum submergence of the pump inlet for satisfactory operation. If the required total net positive suction head is less than the atmospheric pressure, the difference is the permissible suction lift of the pump. Similarly, if the total net positive suction head is greater than the atmospheric pressure, the difference is the minimum depth at which the pump inlet must be submerged below the pumping water level in the well.

The NPSH is a characteristic of the pump. Hence, its value is independent of the atmospheric pressure. The total available NPSH can be increased by placing the pump inlet at a lower level in the well or operating the pump with a higher pumping level in the well.

Negative Pressure

The negative pressure head, also called suction, is the head below the atmospheric pressure head. This draws the fluid into a pipe or pump chamber by producing a partial vacuum, i.e. by reducing the pressure below atmospheric pressure. The water in the well is forced up and into the pump (where the suction has been developed) by the atmospheric pressure acting on the free surface of water in the well.

9.5.2 Maximum Suction Lift

When water is moving into a pump, the maximum suction lift is limited by four factors, i.e. atmospheric pressure, vapour pressure, head loss due to friction and net positive suction head of the pump itself. Thus,

$$H_s = H_a - H_f - e_s - \text{NPSH} - F_s \tag{9.11}$$

where, H_s = maximum practical suction lift, m
H_a = atmospheric pressure at the water surface, m (10.33 m at sea level)
e_s = saturated vapour pressure of water, m
NPSH = net positive suction head of the pump, including, losses at the impeller and velocity head, m
F_s = factor of safety, which is usually taken as 0.6 m

An approximate correction of H_a for altitude is a reduction of 0.36 m for each 300 m in altitude.

Sometimes, suction lift may not occur inspite of perfect vacuum, because of other limiting factors, namely, vapour pressure and pipe friction. Water, like other liquids, has a tendency to change from the liquid into the vapour state. Hence, in all types of pumps, vapour pressure has a limiting effect on the suction lift.

Example 9.2 Determine the maximum practical suction lift for a pump having discharge of 38 1/s. The water temperature is 20 °C. The total friction loss in the 10 cm diameter suction line and fittings is 1.5 m. The pump is operated at an altitude of 300 m above sea level. The NPSH of the pump, as obtained from the characteristic curves supplied by the manufacturer, is 4.7 m.

Solution

Saturated water vapour pressure at 20 °C = 0.24 m (from Standard Physical Tables).

F_s is assumed to be 0.6 m

Atmospheric pressure = 10.33 – 0.36 = 9.97 m

The maximum suction lift is given by

$$\begin{aligned} H_s &= H_a - H_f - e_s - \text{NPSH} - F_s \\ &= 9.97 - 1.5 - 0.24 - 4.70 - 0.6 \\ &= 2.93 \text{ m} \end{aligned}$$

9.6 POWER REQUIREMENTS IN PUMPING

To determine the horse power of the electric motor or engine used in driving a pump, it is necessary to know the efficiency of the pump, the type of drive, the type of power unit, the head under which the pump operates, and the losses in the pumping system.

Water Horse Power (WHP)

Water horse power is the theoretical power required for pumping. It is expressed as

$$\text{WHP} = \frac{\text{Discharge, 1/s} \times \text{Total head, m}}{76}$$

$$= \frac{\text{Discharge, m}^3/s \times \text{Total head, m}}{0.076}$$

Shaft Horse Power

It is the power required at the pump shaft. It is expressed as

$$\text{Shaft horse power} = \frac{\text{Water horse power}}{\text{Pump efficiency}}$$

$$\therefore \quad \text{Pump efficiency} = \frac{\text{Water horse power}}{\text{Shaft horse power}}$$

Brake Horse Power

It is the actual horse power to be supplied by the engine or electric motor for driving a pump. In case of monoblock and other direct-driven pumps, the brake horse power is equal to the shaft horse power, assuming the drive efficiency to be 100 per cent. In case of belt or other indirect drives,

$$\text{Brake horse power} = \frac{\text{Water horse power}}{\text{Pump efficiency} \times \text{Drive efficiency}}$$

Input Horse Power

Input horse power is expressed as follows:

$$\text{IHP} = \frac{\text{Water horse power}}{\text{Pump efficiency} \times \text{Drive efficiency} \times \text{Motor/engine efficiency}}$$

$$\therefore \quad \text{Kilowatt input to electric motor} = \frac{\text{Brake horse power} \times 0.746}{\text{Motor efficiency}}$$

Example 9.3 A pump lifts 100,000 litres of water per hour, against a total head of 20 metres. Compute the water horse power. If the pump has an efficiency of 75 per cent, what size of prime mover is required to operate the pump? If a direct drive electric motor with an efficiency of 80 per cent is used to operate the pump, compute the cost of electrical energy in a month of 30 days. The pump is operated for 12 hours daily for 30 days. The cost of electrical energy is 20 paise per unit.

Solution

$$\text{Water horse power} = \frac{\text{Discharge, 1/s} \times \text{Total head, m}}{76}$$

$$= \frac{100,000 \times 20}{60 \times 60 \times 76}$$

$$= 7.30$$

$$\text{Shaft horse power} = \frac{\text{Water horse power}}{\text{Pump efficiency}}$$

$$= \frac{7.30}{0.75}$$

$$= 9.73$$

Since the pump is direct driven, the shaft horse power is the same as the brake horse power of the prime mover.

$$\text{Kilowatt input to motor} = \frac{\text{BHP} \times 0.746}{\text{Motor efficiency}}$$

$$= \frac{9.73 \times 0.746}{0.80}$$

$$= 9.07$$

Total energy consumption per month = $9.07 \times 12 \times 30$
= 3265 kilowatt-hours (electrical units)

$$\text{Cost of electrical energy} = 3265 \times \frac{20}{100}$$

= Rs 653.00

Example 9.4 A direct driven centrifugal pump coupled to a 3-phase electric motor is installed in a deep open well. The discharge rate of the pump is 20 1/s. The pump efficiency is 70 per cent. The centre line of the pump is 60 cm vertically above the static water level and 6 m above the pumping water level. The suction pipe is 7.5 m long and 8 cm in diameter. A foot valve with strainers is fixed to the bottom of the suction pipe. The suction line is connected to the pump inlet by a long sweep bend of the same size as the suction pipe. The pump discharges water into the top of the pump stand of an underground pipeline water distribution system. The vertical distance between the top of the stand and the centre line of the pump is 20 m. The total length of the 7 cm diameter discharge pipeline is 20 m. The pipe fittings on the discharge side are three long sweep bends, one gate valve and one reflux valve, all of which are of the same size as the discharge pipe.

From the above data, compute

(1) Total head
(2) Water horse power
(3) Brake horse power of the motor required to drive the pump

Solution

Area of suction pipe $a_1 = \frac{\pi}{4} \times \frac{8}{100} \times \frac{8}{100} = 0.005 \text{ m}^2$

Velocity of water in suction pipe

$$v_1 = \frac{Q}{a_1} = \frac{20}{1000 \times 0.005}$$

$$= 4 \text{ m/s}$$

Area of discharge pipe, $a_2 = \frac{\pi}{4} \times \frac{7}{100} \times \frac{7}{100}$

$$= 0.0038 \text{ m}^2$$

Velocity of water in the discharge pipe

$$v_2 = \frac{Q}{a_2} = \frac{20}{1000 \times 0.0038}$$

$$= 5.26 \text{ m/s}$$

(i) Total head = Total suction lift + Total discharge head

Static suction lift = 6 m

Head loss in suction pipe of 8 cm dia. and 7.5 m length

= 2.25 m (Table 9.1)

Head loss in long sweep bend 8 cm dia.

= 0.41 m (Fig. 9.12 and Table 9.1)

$$\text{Head loss in strainer} = K_s \frac{v_1^2}{2g} = 0.95 \times \frac{4 \times 4}{2 \times 9.81}$$

$$= 0.77 \text{ m}$$

$$\text{Head loss in foot valve} = K_f \frac{v_1^2}{2g} = 0.80 \times \frac{4 \times 4}{2 \times 9.81}$$

$$= 0.65 \text{ m}$$

Velocity head (suction line)

$$= \frac{v_1^2}{2g} = \frac{4 \times 4}{2 \times 9.81}$$

$$= 0.81 \text{ m}$$

Total suction lift = 6.00 + 2.25 + 0.77 + 0.65 + 0.81 + 0.41

= 10.89 m

Static discharge head = 20.00 m

Head loss in discharge pipe of 7 cm dia. and 20 m length

$$= \frac{72 \times 20}{100} = 14.4 \text{ m} \qquad \text{(Table 9.1)}$$

Head loss in three long sweep bends, 7 cm dia.

= 2.07 m (Fig. 9.12 and Table 9.1)

Head loss in gate valve of 7 cm dia.

$$= 0.33 \text{ m} \qquad \text{(Fig. 9.12 and Table 9.1)}$$

Head loss in reflux valve (using Eq. (9.3) for foot valve)

$$= K_f \frac{v_2^2}{2g} = 0.8 \times \frac{5.26 \times 5.26}{2 \times 9.81} = 1.12 \text{ m}$$

Velocity head (discharge line)

$$= \frac{v_2^2}{2g} = \frac{5.26 \times 5.26}{2 \times 9.81} = 1.40 \text{ m}$$

$$\text{Total discharge head} = 20.00 + 14.40 + 2.07 + 0.33 + 1.12 + 1.40$$

$$= 39.32 \text{ m}$$

$$\text{Total head} = 10.89 + 39.32 = 50.21 \text{ m}$$

(ii) $$\text{Water horse power} = \frac{20 \times 50.21}{76}$$

$$= 13.21$$

(iii) Brake horse power of motor required to drive the pump

$$= \frac{13.21}{70} \times 100 = 18.87$$

9.7 PUMP CHARACTERISTIC CURVES

Centrifugal pumps have well defined operating properties which vary with the type of pump, manufacturer and model. These properties are expressed as characteristic curves. These curves, also known as performance curves, show the inter-relationship between capacity, head, power and efficiency of a pump at a given speed. A knowledge of the pump characteristics enables the selection of a pump which is best adapted to a particular set of conditions, thus obtaining high value of efficiency at a low operating cost. To illustrate the performance of a pump, it is usual to plot the head, the power input and efficiency as ordinates against the capacity as abscissa, at a constant pump speed (Fig. 9.14). The net positive-suction head, when shown, is also plotted as ordinate (Fig. 9.14). About 6 to 12 values are taken during a pump test to plot the points. Smooth curves are drawn, joining the points.

Head-Capacity Curve

The head-capacity curve (Fig. 9.14) shows how much water the pump will deliver at a given head. As the discharge increases, the head decreases. Thus, the curve will dip downward to the right. When a pump is operated against a closed valve, the head generated is referred to as the shut-off head. The efficiency of the pump at this point is zero as there is no discharge, but the pump requires energy to drive.

Efficiency-Capacity Curve

The efficiency-capacity curve (Fig. 9.14) shows the relationship between the efficiency and the capacity of a pump. The efficiency may be observed to increase from 0, when the discharge is 0, to a maximum, and then decrease. There is generally only one peak efficiency, which is related to a specific capacity. Efficiencies vary with the type of pump, manufacturer and model.

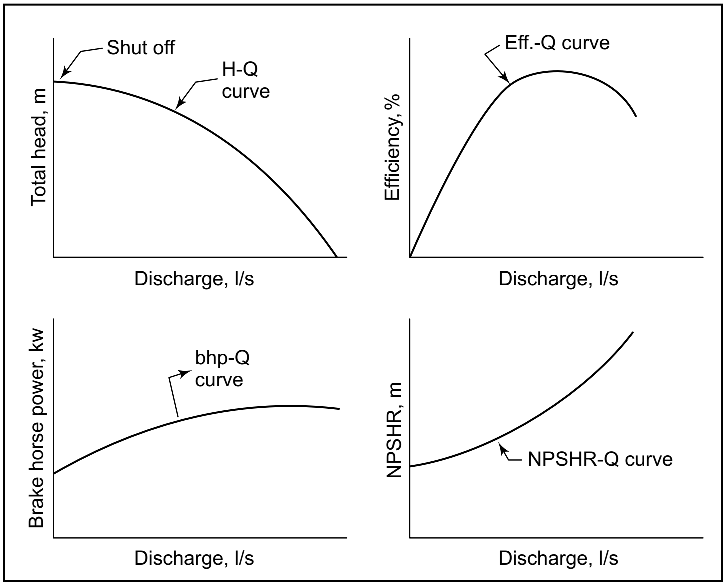


Fig. 9.14 Typical characteristic curves of a centrifugal pump

Input Power-Discharge Curve

The input power is referred to as the brake horse power required to drive a pump. The curve is, therefore, commonly called bhp-*Q* curve (Fig. 9.14). The brake horse power for a centrifugal pump increases as the discharge increases, reaching a peak at a somewhat higher rate of discharge than that which produces the maximum efficiency. The nature of the curve varies with the speed of the pump. Hence, the optimum operating speed must be considered while selecting a pump to obtain high efficiency.

Net Positive Suction Head Versus Discharge Curve

The net positive suction head required versus discharge curve is known as NPSHR-*Q* curve (Fig. 9.14). The NPSHR is the amount of energy required to move the water into the eye of the impeller. It is a function of the pump speed, impeller shape, liquid properties and discharge rate. If the energy is not sufficient to move the water into the eye of the impeller, the liquid will vaporize and cavitation will occur. The net positive suction head available must be more than the net positive suction head required

(NPSHR). Sometimes this curve is missing from the set of characteristic curves supplied by the manufacturers. In such cases, the requirement of the net positive suction head may be ascertained from the manufacturer.

Usually, curves showing different characteristics are plotted on the same graph (Fig. 9.15). Often, several curves representing different pump speeds or impeller diameters are drawn on the same graph.

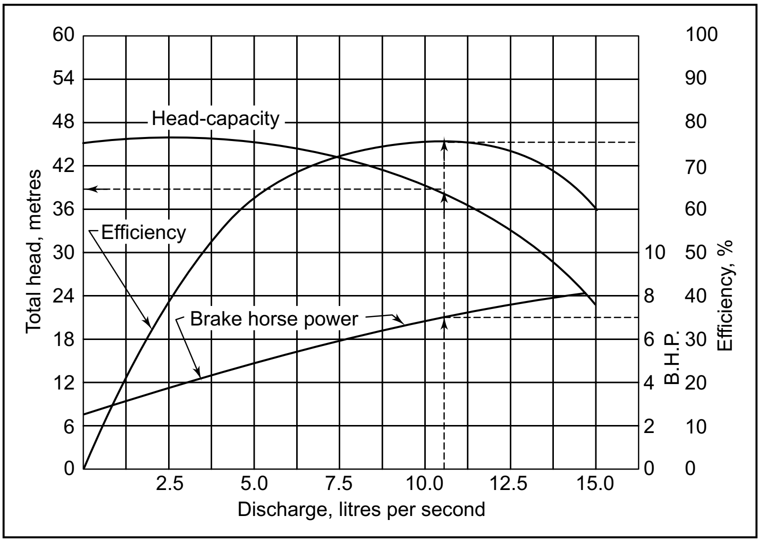


Fig. 9.15 Typical characteristic curves of a centrifugal pump

This type of graph shows a number of head-capacity curves for one impeller diameter and different speeds. Head-capacity curves for different impeller diameters and one speed are also available. A family of curves showing the above relationships is known as a composite characteristic curve (Fig. 9.16). When this is available, iso-efficiency lines are plotted by joining points of equal efficiency on the head-capacity curves.

Sometimes composite curves of different pumps are plotted on the same graph, showing the relationship between their heads, and capacities (Fig. 9.17). The model of the pump and the requirement of power (kW) are indicated with respect to each curve. The pump giving the desired capacity and satisfying the required operating head and providing the safe yield of the well (or other source of water) and having the minimum power requirement is selected out of these curves.

The method of reading a performance curve is the same as for any other graph. For example, in Fig. 9.15, it is desired to determine the head, horse power and efficiency of a pump at a capacity of 10.6 1/s. By reading the graph, as illustrated by the dotted line, it is observed that at 10.6 1/s, the pump will develop a 38 m head. The corresponding requirement of horse power is 7.1 and the efficiency is 75.5 per cent.

The composite characteristic curve shown in Fig. 9.16 are read in the same way as the simple curves shown in Fig. 9.15. For example, suppose it is required to select a pump and power unit capable of delivering water at the rate of 16 1/s against a head of 30 m. It is important to select a pump that will operate near its highest efficiency most of the time. From Fig. 9.16, it is observed that the above

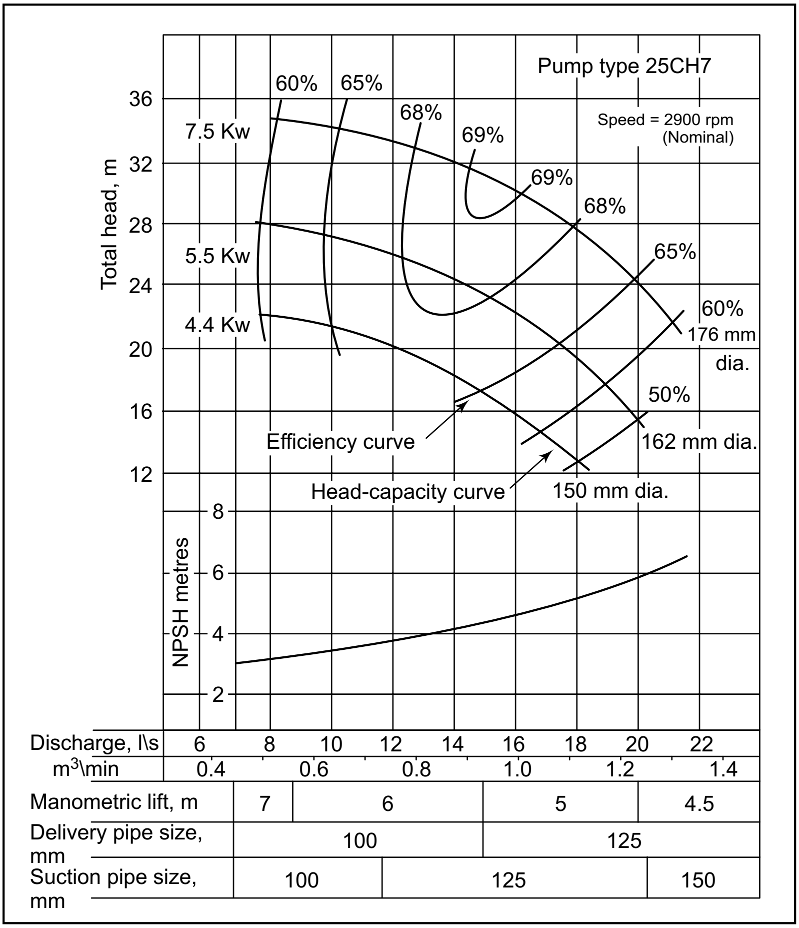


Fig. 9.16 Composite characteristic curves of a centrifugal pump with different impeller diameters
Adapted from: Kirloskar Bros. Ltd. Kirloskarvadi, Distt. Sangli

conditions are met by selecting a pump with an impeller diameter of 176 mm. It will then operate at its highest efficiency of 69 per cent. The power requirement at the point is above 5.5 kW and below 7.5 kW. Hence, a 7.5 kW electric motor is selected. A more exact value of the power required may be computed from the values of head, capacity and efficiency, using the relationship presented earlier in this chapter. The corresponding suction lift is read as 5 m and the size of the delivery and suction pipes as 125 mm. If the composite graph presents the pump characteristics at different speeds, the best operating speed along with the other factors are selected in the way explained above. Many operating points will fall between various curves. Therefore, it is necessary to understand a composite curve well enough to interpolate and determine the approximate values required.

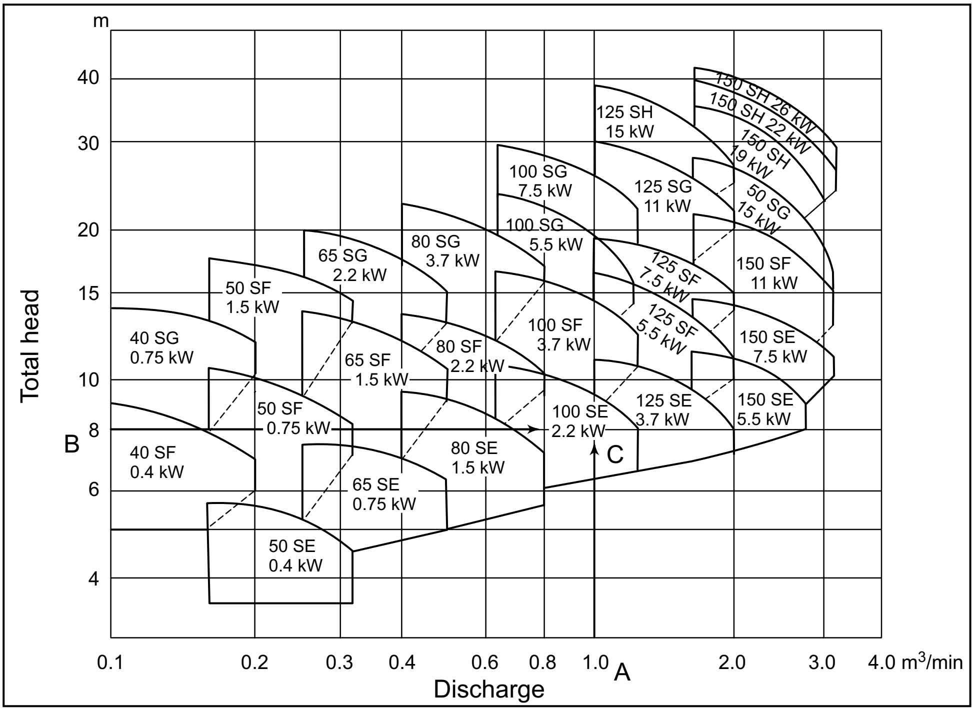


Fig. 9.17 Composite characteristic curves for various models of pumps
Courtesy: Ebara Manufacturing Co. Ltd., Tokyo, Japan (Anon., 1970).

Characteristic Curves for Pumps in Series

In case of a multi-stage pumping operation, two or more pumps are connected and operated in series. In other words, the single stages are connected in series. The discharge from the first stage is pumped to the second stage, and so on. The same discharge passes through all the stages. This arrangement is essential when the head required is more than that can be produced with a single pump. The same discharge passes through all the stages. Each stage adds an additional head to the fluid. Thus, the combined head of two pumps operating in series is equal to the sum of the individual heads, for a specific discharge (Fig. 9.18). For different values of discharge, the combined head is obtained from the individual head-capacity curves for pumps 1 and 2. A new head-capacity

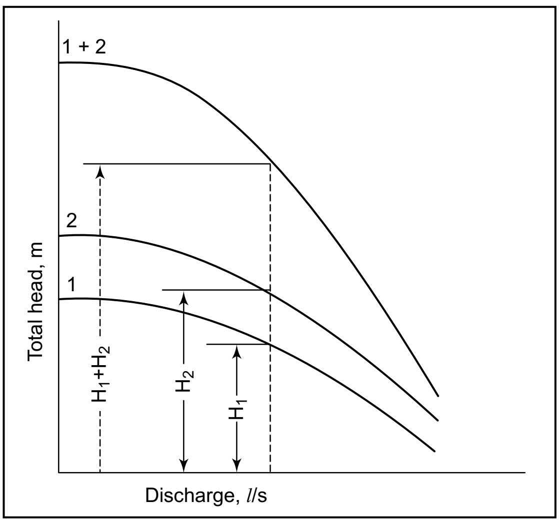


Fig. 9.18 Head characteristic curves of two pumps operating in series

curve is plotted, giving the relationship between the sum of the heads of each pump and the corresponding discharge. In this case, the discharge $Q = Q_1 = Q_2$, while the total head $H = h_1 + h_2$. The combined input energy is the sum of the input energies for each pump. The combined efficiency (Jensen, 1980) is given by the following relationship:

$$E_{\text{series}} = \frac{Q\,(h_1 + h_2)}{102\,(\text{BHP}_1 + \text{BHP}_2)} \qquad (9.12)$$

where, Q = discharge capacity, 1/s
h_1 = total head for pump 1, m
h_2 = total head for pump 2, m
BHP_1 = brake horse power for pump 1, kW
BHP_2 = brake horse power for pump 2, kW

Characteristic Curves of Pumps Operating in Parallel

Sometimes water pumps are installed in parallel, as in the case of pumping water from a sump well using more than one pump. The head remains constant. The combined discharge of the two pumps operating in parallel is equal to the sum of the individual discharges for a specific head. For different values of head, the combined discharge is obtained from the individual head-capacity curves for pumps 1 and 2. A new head-capacity curve is plotted, giving the relationship between the sum of the discharges of each pump and the corresponding head. In this case

$$H = h_1 = h_2$$

The total discharge

$$Q = Q_1 + Q_2$$

The combined efficiency is given by the following relationship (Jensen, 1980):

$$E_{\text{parallel}} = \frac{(Q_1 + Q_2)\,H}{102\,(\text{BHP}_1 + \text{BHP}_2)} \qquad (9.13)$$

where, Q_1 = discharge capacity of pump 1, 1/s
Q_2 = discharge capacity of pump 2, 1/s
H = total head, m
BHP_1 = brake horse power for pump 1, kW
BHP_2 = brake horse power for pump 2, kW

Pump Performance

The performance of a pump depends upon its design and installation. The desired efficiency can be obtained by correctly designing the different components of the pump and obtaining a high degree of precision in the manufacture.

The performance of centrifugal pumps can be changed by changing the impeller diameter or speed using the Affinity Laws. The Affinity Laws are mathematical expressions that define changes in pump capacity, head and BHP when a change is made to pump speed, impeller diameter or both.

Effect of Change of Pump Speed on Pump Performance

When the speed of a centrifugal pump is changed, the performance of the pump is changed as follows:
(i) The capacity varies directly as the speed
(ii) The head varies as the square of the speed
(iii) The brake horse power varies as the cube of the speed.

Expressed mathematically,

$$Q = Q_1\left(\frac{n}{n_1}\right) \tag{9.14}$$

$$H = H_1\left(\frac{n}{n_1}\right)^2 \tag{9.15}$$

$$P = P_1\left(\frac{n}{n_1}\right)^3 \tag{9.16}$$

or

$$\frac{n}{n_1} = \frac{Q}{Q_1} = \sqrt{\frac{H}{H_1}} = 3\sqrt{\frac{P}{P_1}} \tag{9.17}$$

where, n = new speed desired, rpm
Q = capacity at the desired speed n, 1/s
H = head at the desired speed n for capacity Q, m
P = BHP at the desired speed n at H and Q, hp
n_1 = speed at which the characteristics are known, rpm
Q_1 = pump capacity at speed n_1, 1/s
H_1 = head at capacity Q_1 and speed n_1, m
P_1 = BHP at speed n_1 at H_1 and Q_1, hp

Effect of Change of Impeller Diameter

Changing the impeller diameter has the same effect on pump performance as changing the speed. Therefore, the following relationship apply:

(i) The capacity varies directly as the diameter
(ii) The head varies as the square of the diameter
(iii) The brake horse power varies as the cube of the diameter.

Expressed mathematically,

$$Q = Q_1\left(\frac{D}{D_1}\right) \tag{9.18}$$

$$H = H_1\left(\frac{D}{D_1}\right)^2 \tag{9.19}$$

$$P = P_1\left(\frac{D}{D_1}\right)^3 \tag{9.20}$$

or
$$\frac{D}{D_1} = \frac{Q}{Q_1} = \sqrt{\frac{H}{H_1}} = 3\sqrt{\frac{P}{P_1}} \tag{9.21}$$

where, D = change diameter of the impeller, mm

D_1 = original diameter of the impeller, mm

The other terms are the same as used in Eq. (9.17).

When pumps are driven by belts or other variable-speed drives, it is possible to change the operating speed. However, many pumps are directly coupled to electric motors or engines, and must run at constant speed. In this case, it is necessary to change the impeller diameter to alter the pump performance.

If changes are made to both impeller diameter and pump speed the equations can be combined to:

$$Q = Q_1 \times \left(\frac{D \times n}{D_1 \times n_1}\right) \tag{9.22}$$

9.8 SYSTEM HEAD CURVE

The system head curve gives the relationship between the discharge and the total head in a pumping system (Fig. 9.19). It shows that more head is required to increase the discharge through the system. The contribution of various parameters to the total head, and their variation with increase in discharge is illustrated in Fig. 9.19. The static suction lift and the static discharge head are independent of the discharge rate, but might change with time. For example, a change in the water table or the point of use would change the static suction lift and the static delivery head, respectively.

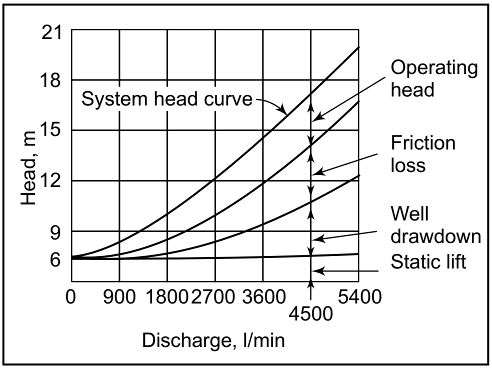


Fig. 9.19 A typical system head curve

The drawdown of a well is a function of the discharge rate, the well radius, the duration of operation of the pump, and aquifer properties. The drawdown may be calculated using the standard equations in well hydraulics. However, the best way to determine the relationship between discharge and drawdown is through a pumping test. The well is operated at various rates of discharge and the corresponding drawdown is observed. The pump is operated at a constant discharge for a sufficiently long time, so that the drawdown stabilizes. Usually, well testing is started with the highest flow rate and pumping is continued until the discharge gets stabilized and, successively, the pumping rate is reduced. This procedure would result in attaining equilibrium conditions in a short time for the lower discharge rates.

There is loss of head due to friction when the water flows through the piping system, as the pump is required to add energy to overcome friction loss (Sec. 9.3). An increase in discharge results in a linear increase in velocity, leading to an increase in friction loss, which is a function of the square of the velocity.

The total head shown in Fig. 9.19 does not include the operating pressure or head, because it is assumed that the water is discharged directly into an open ditch. However, the operating pressure is to be taken into account when the pumping set is used to lift water to a pressure tank or is operating sprinkler or drip irrigation systems. The operating pressure may increase continuously or step by step, depending upon the operating conditions. When an operating head exists, it is included in the total head.

The system head curve is time dependent because of variation in static suction head, well draw-down, operating conditions and friction losses (friction losses may increase in old steel pipes due to wear and salt deposits and because of salt deposits in case of PVC pipes). Therefore, while selecting a pump the change in pumping conditions over the anticipated service life of the pump should be considered.

9.9 SELECTION OF CENTRIFUGAL PUMPS

Several thousand centrifugal pumps are manufactured, by a large number of manufacturers, in almost every country. These pumps are available in a wide range of sizes and have widely varying characteristics. The selection of the right type of pump will require a knowledge of the use of the system head and pump characteristics curves described in Articles 9.7 and 9.8. The normal procedure for selecting a pump is to first determine the system head curves and desired discharge. The characteristic curves or tables giving the performance of various models of pumps are used to select the right type of pump, which will operate efficiently at or near the desired discharge, and the system's total dynamic head. The procedure for determining the total head has been described in See. 9.4.

Determining the Discharge Capacity of Pumps

The data on the safe discharge rate of the well (or other source of water) and the discharge rate required for the crops to be irrigated with a particular cropping pattern are estimated. If necessary, the cropping pattern can be adjusted according to the safe yield of the well in different seasons. In many cases, such adjustments may not be possible on one's own farm, as the holding may be smaller than the command area required by a pump of moderate size. In some cases, the holding may be fragmented and only a few fragments belonging to the farmer are within the service orbit of a pump of moderate size. In such cases, any one of the following alternatives can be adopted:

1. Design the pumping plant according to the safe yield of the well and operate it for a limited time to meet the requirement of an individual farmer, keeping the well and the pump idle for the rest of the period. However, it leads to high investment and under-utilization of the installed capacity, investment of funds and available ground water resources.
2. Design the pumping plant according to the safe yield of the well, use the installed capacity to irrigate one's own land and sell the remaining water to neighbouring farmers. This alternative is better than the first and leads to full utilization of the ground water potential, the development of which requires large investments.

   Thus, a pumping set should be designed with respect to two factors, (i) the safe yield of the well, and (ii) the maximum water requirement of the crops per day in peak periods. The factor that dominates the situation should be considered in calculating the size of the pump and, consequently, efforts should be made to adjust the other factor within possible limits so as to have efficient utilization of the resource potential. In such computations, due regard should be given to the efficiency of the water conveyance system in the fields.

3. In pumping from rivers and canals, if there is no constraint on the availability of water, the pump capacity may be determined on the basis of the water requirement of the crops to be grown by a farmer, or group of farmers of a cooperative lift irrigation scheme.

Determining the Safe Yield of Wells

Procedures for testing the yield of wells and the limiting conditions in pumping from a well are described in Ch. 6. In places where the facility for testing the yield of wells is not available, a fair estimate of safe yield may be made by observing the discharge rates of neighbouring wells under nearly identical hydrological situations.

Discharge Capacity of Pumps based on Crop Requirements

The pump discharge should meet the peak demand of water for a selected cropping pattern. The rate of pumping depends on the area under different crops, the water requirement of the crops, the rotation period (interval between two successive irrigations of a crop), and the duration the pump is operated each day. It may be computed by the following relationship:

$$Q = \frac{27.78}{T} \sum_{n=1}^{n} \frac{A_n Y_n}{R_n} \tag{9.23}$$

where, Q = rate of discharge of pumps, 1/s
A_n = area of land under n^{th} crop, $n = 1$ to n, ha
Y_n = depth of irrigation for n^{th} crop, cm
R_n = rotation period, i.e. irrigation interval for the n^{th} crop, days
T = duration of pumping, h/day

Example 9.5 A farmer wishes to have his own pumping set for the following cropping pattern, to be followed in his holding of 3 ha. Calcualte the right size of the centrifugal pump he should have. The crops proposed to be grown in different seasons, depth of irrigation, rotation periods, and the duration of operation of the pump are as follows:

Season	Crop	Area to be irrigated, ha	Irrigation depth per irrigation, cm	Rotation period Days	Period of work hours/day
Winter (*rabi*)	Wheat	3	7.5	15	10
Summer	Maize	1	7.5	20	10
(*kharif*)	Paddy	2	5.0	2	10

Solution
Irrigation requirement for the winter crop:

$$Q = 27.78 \times \frac{3 \times 7.5}{15 \times 10} = 4.17 \text{ 1/s}$$

Irrigation requirement for the monsoon crop (*kharif*):

$$Q = 27.78 \times \left\{ \frac{1 \times 7.5}{20 \times 10} + \frac{2 \times 5.0}{2 \times 10} \right\} = 14.93 \text{ l/s}$$

Therefore, the capacity of the pump required for meeting the maximum water requirement of the crops (summer season crops) is 14.93 l/s.

To allow for the conveyance losses of water between the pumps and the field, the pump capacity may be increased by about 20 per cent. Hence, the discharge rate required by the pump = 14.93 × 1.20 = 17.92 l/s.

The irrigation requirements of crops vary from region to region, depending on the characteristics of the crop, the type of soil, and climatic conditions. The water requirements of the crops in a particular area should be estimated on the basis of the information applicable to that area.

Procedure for Selection of Centrifugal Pumps

A centrifugal pump is designed to operate efficiently within a specified range of capacity and total head. When applied to a different set of conditions, the same pump will not work efficiently, irrespective of the amount of power applied to operate it. Therefore, by matching the system head curve or curves for a range of discharges above the design discharge rate, with the characteristics of various models of pumps, the right type of pump giving the maximum efficiency can be selected. Alternatively, when the pump characteristics are given as tabular data, the pump which requires the minimum power to operate at the design total head and capacity is to be selected, after comparing the data from several reputed manufacturers.

Matching Pump Characteristics and System Head Curves

Matching the system head curves and the pump characteristic curves enables selection of the pump which suits the source of water. It is usual to draw the system head curve on a tracing paper, on the same scale as the pump characteristics curve. The tracing paper is placed on the graph showing the pump characteristics. The characteristics of the pumps manufactured by leading manufacturers are matched with the system head curve. This will lead to the selection of the pump which gives the maximum efficiency and the desired discharge at the estimated total head. Figure 9.20 shows the matching of the characteristics curves of a pump with the system head curve. The point of intersection of the head capacity curve of the pump and the system head curve provides a point of selection. At this point, the pump will give a discharge of 3150

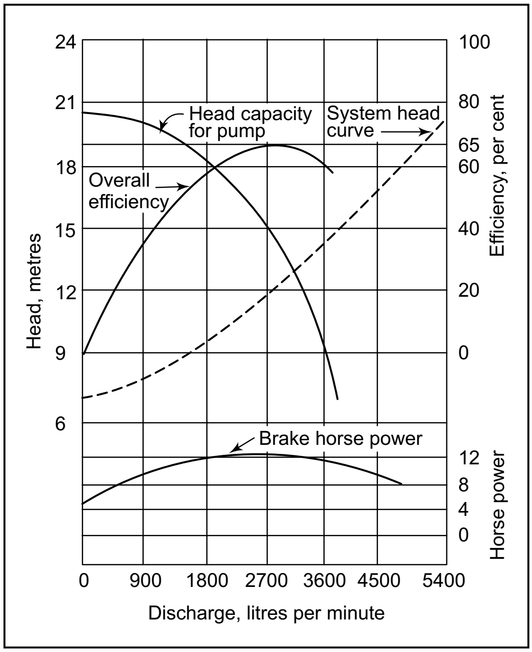


Fig. 9.20 Matching the pump characteristic curves with system head curve

1/min against a total head of 13 m and an efficiency of 65 per cent. The power input is 12 hp. By careful selection from a wide range of products, it is possible to select a pump which will give the desired discharge rate at the estimated total head and provide an efficiency of 75-80 per cent or more.

Referring to Fig. 9.20, the discharge decreases as the required head increases, and vice versa. The discharge will be reduced to 2700 1/min if the head is increased to 15 m. Similarly, if the head is decreased to 9 m, the discharge will be increased to 3600 1/min. Thus, the change in the operating head influences the discharge of a pump. Therefore, under fluctuating water table conditions, the pump selected should result in a minimum variation in discharge with change in operating heads.

Selecting Number of Stages

Multi-stage pumps are used when the required head cannot be developed by a single stage. The number of stages is equal to the total head divided by the head developed by a single stage pump. However, the head developed by a single stage is different for different types and models of pumps. Therefore, the selection of the right type of multi-stage pump becomes important. The selection procedure is similar to that for a single-stage pump, for a given system head curve and design discharge.

The procedure for obtaining the characteristic curves for two or more pumps operating in series has been described in Art. 9.7. The performance of multi-stage pumps can be evaluated by superimposing these curves on system head curve.

The selection procedure of a multi-stage pump is given in Fig. 9.21. The head-capacity curves for pumps 1 and 2 and the single-system head curve have been drawn. The design discharge is 50 1/s, with

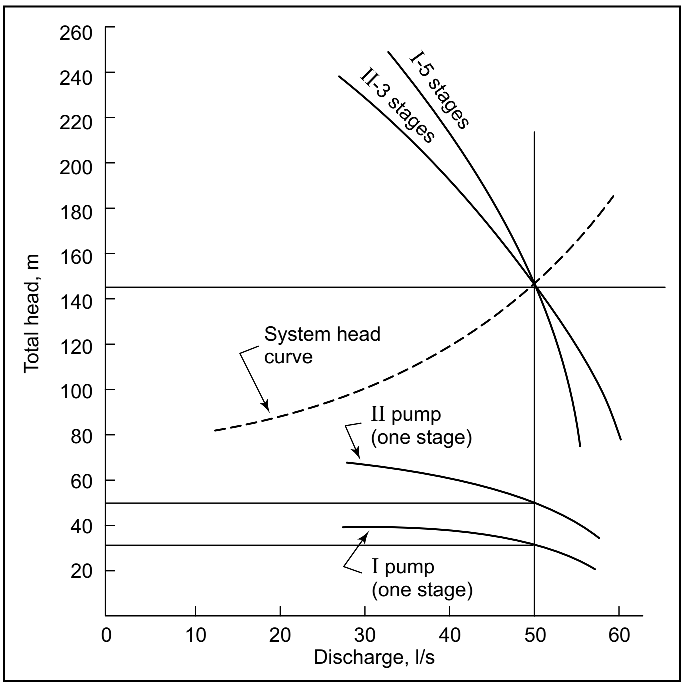


Fig. 9.21 Development of head-capacity curves for selection of multi-stage pumps

a required dynamic head of 150 m. In case of pump I, a single stage can develop a head of 30 m for the design discharge of 50 1/s. Therefore, the pump would require five stages. For pump II, a single stage develops a head of 50 m at 50 1/s. Therefore, the number of stages required would be 3. The head capacity curves developed for pumps I and II, for the desired number of stages, are shown in Fig. 9.21. Pump 1 with 5 stages is selected because the combined head capacity curve is steeper, which will result in less variation in discharge with the change in operating head. Referring to Fig. 9.21, if the total head increases to 160 m, the discharge reduces to 48.75 1/min and 47.50 1/min for pumps I and II, respectively. It may be noted that the head-capacity curve for a single stage was steeper in pump II, while for multi-stage it is steeper for pump I, because the slope of a multi-stage head-capacity curve depends on both the number of stages and the slope of the single-stage curve.

Example 9.6 The characteristic curves for pumps of various models, manufactured by a standard company, are given in Fig. 9.17. Select a suitable pump capable of giving a discharge of 1 m^3/min under an operating head of 8 m.

Solution

The characteristics curves give the relationship between capacity and head for the various models of pumps. The capacity is plotted on the horizontal scale and head on a vertical scale. The required capacity and head are marked on the horizontal and vertical scales, at points A and B, respectively. Straight lines (dotted) are drawn through points A and B, parallel to the vertical and horizontal axes, respectively, meeting at point C. The point of intersection show the right type of pump, which is the pump model SE of 100 mm suction diameter requiring 2.2 kW of power.

Example 9.7 Select a suitable monoblock pumping set capable of delivering a discharge of 20 1/s for an operating head of 14 m. The characteristics of a series of pumps of one of the leading manufacturers are given in Table 9.3.

Solution

Capacity = 20 *l*/s

Total head = 14 m

Referring to Table 9.3, the KS-2 type pump of 80 mm × 65 mm size is suitable for delivering a discharge of 21 *l*/s at a head of 14 m. It may be seen from Table 9.3 that even if the head increases to 16 m there will not be any appreciable decrease in discharge. The required horse power of the electric motor is 5. Alternatively, the pump type KS-4 of 100 mm × 100 mm size can be chosen. This pump would provide a discharge of 20 *l*/s at 14 m head. The power requirement is 5 hp. However, in this case, if the operating head increases to 15 m, the pump capacity gets reduced from 20 *l*/s to 14.5 *l*/s. Hence, the first pump is more suitable than the second, under conditions of fluctuating water table (*Note*: In actual practice, however, it is not desirable to limit the selection from the types of pumps available with a particular manufacturer. Most manufacturers do not have pumps which suit every possible requirement. There is also variation in the cost of pumps of different makes. Hence, it is necessary to obtain information on the characteristics of pumps manufactured by different manufacturers and select the one which is most efficient and least expensive).

Example 9.8 A volute centrifugal pump driven by an electric motor is to be selected to lift water from an open well which has its pumping water level ranging from 8-10 m below ground level. The delivery head of the pump is 8 m. The head loss due to friction in the pipeline and fittings amounts to 2 m. The discharge capacity of the well range from 25-30 *l*/s during the irrigating seasons. Table 9.4 is

TABLE 9.3 Performance Characteristics of the Monoblock Pumping Set (1450 rpm) of a Leading Manufacturer for Pump Selection in Example 9.7

Type of Pump	Size mm	Impeller diameter mm	Total head, m															Size of matching electric motor, hp
			6	8	10	12	13	14	15	16	18	20	22	24	26	27	28	
			Pump discharge, l/s															
KS-1	50 × 40	225	—	—	8.8	7.9	7.4	6.7	6.1	5.25	2.7	—	—	—	—	—	—	2
KS-1	65 × 50	225	—	—	—	16	14	13	11.5	9.5	—	—	—	—	—	—	—	3
KS-1	65 × 50	243	—	—	—	—	—	—	—	—	10.25	6.5	—	—	—	—	—	4
KS-2	80 × 65	245	—	—	—	23	22	21	20.8	18.5	15.5	11.5	—	—	—	—	—	5
KS-2A	80 × 65	200	—	—	18	15	13	10	—	—	—	—	—	—	—	—		3
KS-3	65 × 50	266	—	—	—	—	—	—	—	—	15.5	13	10.5	7	—	—	—	5
KS-3	65 × 50	274	—	—	—	—	—	—	—	—	—	—	—	10.8	7.5	5	—	5
KS-4	100 × 100	208	36	33	33	26	23	20	14.5	—	—	—	—	—	—	—		5
KS-4A	100 × 100	182	26	22.2	16.2	—	—	—	—	—	—	—	—	15.7	14.5	13.5	12.2	7.5
KS-6	80 × 80	—	—	—	—	—	—	—	—	—	—	17	16.5	—	—	—	—	7.5

TABLE 9.4 Abstract of Tabular Data on the Performance of Pumps offered by Different Manufacturers for Selection of the Pumps in Example 9.8

Name of manufac-turer	Pump code no.	Pump size mm × mm	Impeller diameter mm	Total head, m							hp reqd.	Speed rpm
				14	16	18	20	22	24	26		
				Pump discharge, 1/s								
A	4 MK 2	80 × 100	280	—	—	29.4	25.0	20.6	14.0	—	12.5	1500
	4 MK3	80 × 125		—	—	32.0	30.4	28.4	26.5	24.0	15.0	1500
	4 MK 3	100 × 125	273	41.0	36.0	31.0	27.0	20.0	—	—	12.5	1500
	2 MK 4	100 × 100	144	26.5	20.5	—	—	—	—	—	10.0	1450
B	2 SM 2	100 × 100	212	31.0	29.5	27.5	25.5	23.0	20.0	16.5	11.5	1800
	2 SM 3	100 × 80	240	34.5	33.2	31.5	29.5	27.5	25.0	22.5	14.0	1800
	2 SM 4	100 × 80	255	28.5	26.0	23.5	21.0	17.8	12.0	—	10.0	1800
	3 SM 1	80 × 65	245	28.0	27.2	26.4	25.3	24.2	23.0	21.6	11.5	1800
	5 KL 1	100 × 100	212	36.0	34.0	31.0	28.0	22.0	—	—	12.5	2000
C	5 CB 1	100 × 100	186	—	—	34.0	32.5	29.5	25.7	19.0	20.0	2900
	4 CB 2	80 × 100	180	—	—	28.0	26.5	25.0	22.7	19.0	15.0	2900
	3 KZ 1	100 × 100	215	26.0	22.3	19.7	15.1	—	—	—	6.5	1700
	3 KZ 1	100 × 100	215	27.6	25.0	24.2	21.2	18.2	—	—	7.5	1800
	3 KZ 2	100 × 100	215	30.0	28.0	25.7	23.8	16.7	—	—	8.8	1900
	3 KZ 3	100 × 100	215	33.4	31.8	29.5	23.8	24.7	21.2	16.0	10.2	2000
D	2 XY 2	100 × 100	210			20-28 1/s at heads 12 to 20 m					12.5	1500
	2 XY 3	100 × 125	195			20 to 30 1/s at heads 12 to 20 m					12.5	1700

a compilation of the extracts of tabular data on pump performance obtained from the catalogues of reputed pump manufacturers. Select the most suitable pump for the job from the available catalogues.

Solution
The pump should have a discharge capacity from 25-30 1/s, against a total head of 18–20 m. Refering to Table 9.4, the following are the possible selections closely matching the requirements:

Manufacturer	Pump code No.	hp
A	4 MK 3	12.5
B	2 SM 4	11.5
B	3 SM 1	11.5
B	5 KL 1	12.5
C	3 KZ 2	8.8
C	3 KZ 3	10.2

The pump of code No. 3 KZ 3 offered by *C* is probably the best matching unit and requires the minimum horse power. With a slight reduction in capacity, pump of code No. 3 KZ 2 which requires the lowest power could also be selected. The data presented by *D* is incomplete to make a judicious selection of a pump.

Pump Selection Based on Types

The relative merits and applicability of different types of pumps were discussed earlier. Volute centrifugal pumps are adapted to a wide range of head-discharge conditions. As compared to turbine pumps and propeller pumps. The efficiency of vertical turbine pumps, including submersible pumps and propeller pumps, drops rapidly when applied under conditions different from those for which they are designed. Table 9.5 presents the suitability of common types of irrigation pumps to specific pumping situations.

9.10 ACCESSORIES FOR HORIZONTAL VOLUTE CENTRIFUGAL PUMPS

The accessories required for the installation of horizontal volute centrifugal pumps include foot valves, reflux valves, pipes and pipe fittings. Accessories are important components of the pumping plant and contribute substantially to the performance of the pumping system. Unfortunately, little attention was being given to them till recently. Studies in leading research institutions in India have revealed that a major cause of inefficiency in pumping plants has been the use of improper accessories. Hence, the selection of the right type of accessories and their correct location in the suction/delivery lines are as important as the selection of the pump and the prime mover.

9.10.1 Foot Valve

The foot valve (Fig. 9.22) is an integral component of a centrifugal pump installed to lift water from open wells, rivers, canals and ponds. The valve is fixed at the bottom of the suction pipe. It keeps the centrifugal pump primed and restricts the entry of foreign matter, especially floating debris and aquatic

TABLE 9.5 Suitability of Common Types of Irrigation Pumps to Specific Pumping Applications

Source of water	Lift	Yield	Suitable pump type	Remarks
Stream/canal	< 2.5 m	High	Propeller pump	Volute centrifugal pumps inefficient at low heads
Stream/canal	3-12 m	High	Mixed-flow pump	Volute centrifugal pumps also provide satisfactory efficiency at heads > 6 m. Tractor-operated pumps feasible upto about 6 m lift
Stream/canal	> 12 m	Medium to high	Volute centrifugal pump	Multi-stage pumps to be preferred for high beads
Shallow open well	3–6 m	Medium	Mixed-flow/volute centrifugal pump	Pump located at ground surface
Deep open well (electricity available)	> 6 m	Medium	Volute centrifugal pump directly coupled to electric motor	Pumping set located close to water table in well
Deep open well (electricity not available)	> 6 m	Medium	Volute centrifugal pump driven by diesel engine	Engine located at or near ground level, pump driven through belt/shaft
Deep open well (electricity not available)	> 6 m	Low	Jet pump coupled to diesel engine	Pumping set located at ground surface
Sewage pumping	< 6 m	Medium	Non-clog centrifugal pump coupled to electric motor/engine	Pumping set located at ground surface
Shallow tube well/ filter point	< 6 m	Medium	Volute centrifugal pump	Pump driven by electric motor or diesel engine located at ground surface

(*Contd.*)

TABLE 9.5 (*Contd.*)

Source of water	Lift	Yield	Suitable pump type	Remarks
Shallow tube well	5-15 m	Medium	Volute centrifugal pump installed in sump within suction and water table limits	In case of engine drive, the pump is located in a sump while the engine is at the ground surface
Deep tube well (electricity available)	> 15 m	Medium/ high	Submersible pump/vertical turbine pump	Assured service facility essential, especially in case of submersible pump
Deep tube well (electricity not available)	> 15 m	Medium/ high	Deep well turbine pump	Engine located at ground surface
Pumping from sump/drainage pumping	< 6 m	High	(i) Propeller pump for lifts < 2.5 m (ii) Mixed-flow pumps for lifts > 2.5 m	Motor-driven pumps to be provided with float-controlled automatic switch
Canal lifts	< 15 m	High	Mixed-flow pumps	To lift the flow of a canal from a lower to higher elevation

plants, into the suction pipe. Hence, a strainer forms an essential component of a foot valve. The valve is a one-way flap piece made of leather or rubber and hinged to the valve body. When the pump is not working, the valve rests on a well-machined base plate and prevents the return flow of water to the well or other source. Thus, water is retained in the pump casing and suction pipe, thereby eliminating the need for repeated priming of the pump every time it is started.

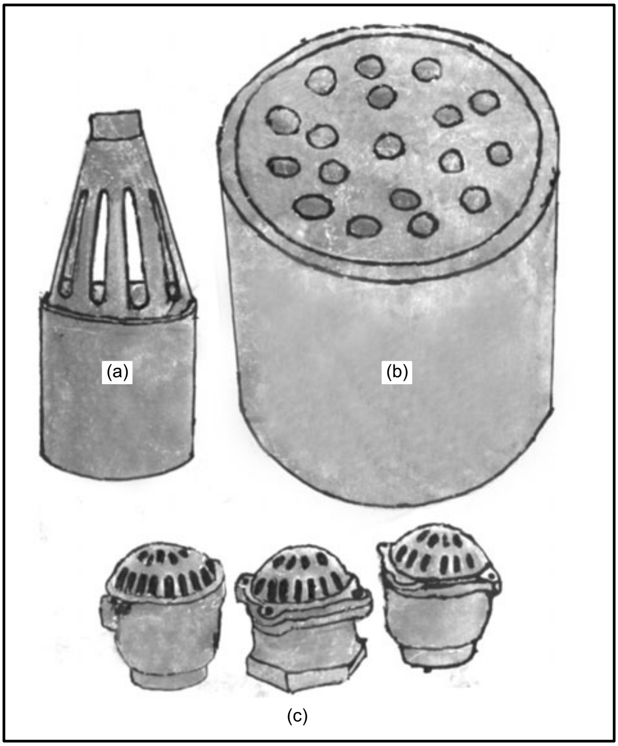


Fig. 9.22 A set of commercially available foot valves with various degrees of efficiency. (a) Valve with cone-shaped strainer, (b) Flat bottom strainer (highly inefficient due to the small area of openings), (c) Valves with dome-shaped strainer. Note that the openings in the valve are partly blocked due to poor manufacturing.

The performance of commercially available foot valves (Figs. 9.22 to 9.25) varies widely. The specifications of foot valves and reflux valves for agricultural pumping systems is given in IS : 10805-1986. The above standard also prescribes the code of practice for testing foot valves. An improperly selected foot valve adversely affects the performance of the pumping unit. There is substantial loss of energy due to excessive friction in the strainer and valve sections of an inadequatey designed foot valve. Such valves increase the total suction head, which has a profound influence on pump performance. The discharge capacity of pumps gets greatly reduced and the energy requirement is increased. The following are the basic requirements of an efficient foot valve (Ram *et al.*, 1982):

1. The total area of the openings in a strainer should be such that the velocity head is minimum. In any case, it should be more than the cross-sectional area of the suction pipe. An optimum value of the ratio of the cross-section of the suction pipe and the total open area of perforations in the strainer is 1 : 3.

2. The strainer should have smooth slotted perforations which are properly streamlined to reduce turbulence of flow into it. (It was observed that slotted perforations give a better hydraulic performance as compared to circular holes.)
3. The area of opening of the base plate on which the valve rests should be equal to or more than the area of the suction pipe.
4. The valve should be so hinged that it opens nearly full.
5. The valve should be leak-proof when closed.

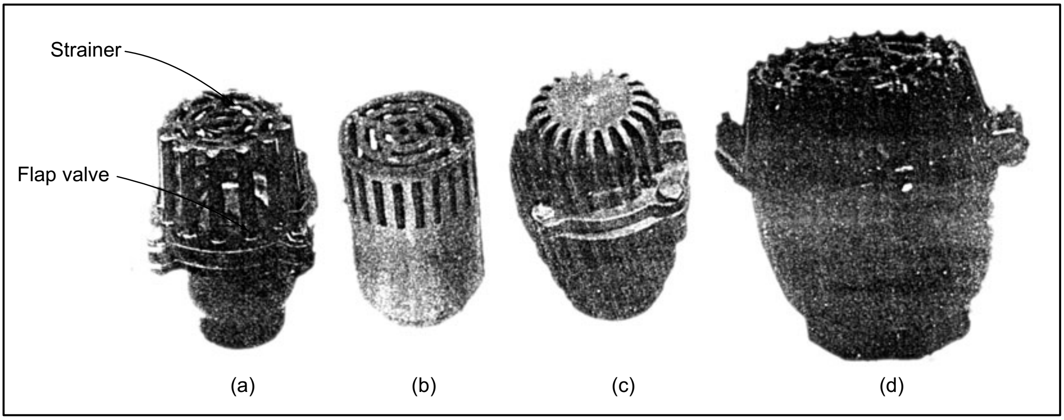


Fig. 9.23 A set of commercially available efficient foot valves: (a) Sujala foot valve (ICM, Ahmedabad), (b) Pantnagar foot valve (G.B. Pant Univ. of Agri. & Tech., Pantnagar), (c) Jyoti plastic foot valve (Jyoti Plastic Works, Mumbai), (d) Kirloskar foot valve (Kirloskar Bros., Pune).

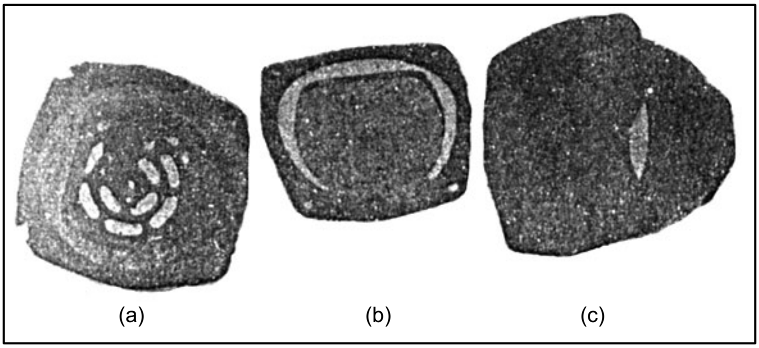


Fig. 9.24 Exploded view of the foot valve shown in Fig. 9.23 (d): (a) Upper casing, (b) Flap valve, (c) Strainer

Friction Loss in Foot Valves

The head loss due to friction in the foot valve of a pump is expressed as follows:

$$H_f = K\frac{V^2}{2g} \tag{9.24}$$

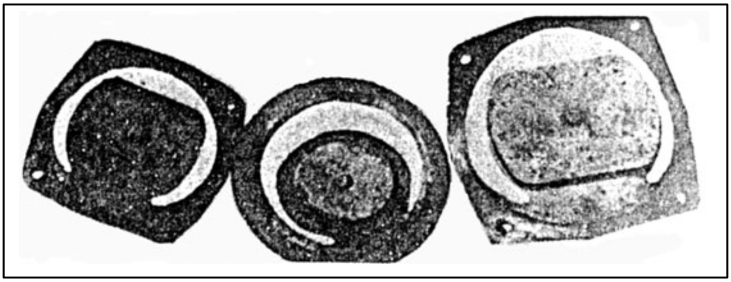


Fig. 9.25 Different types of flap valves used in foot valves. The valve at the centre is of rubber while those on either side are of leather. Note the deterioration in the rubber valve due to usage

where, H_f = head loss in foot valve due to friction, m
K = coefficient of friction for foot valve, dimensionless
g = acceleration due to gravity, m/s^2
V = velocity of flow in the suction pipe, m/s

The head loss and the corresponding friction coefficient vary with the smoothness of the material and the design of the valve and the strainer. Their values have been reported by several agencies. Patel and Gupta (1979) reported the test results of 10 different makes of foot valves. The values of K varied from 2.25 to 13.9. The Punjab Agricultural University, Ludhiana (Sondhi, *et al.* 1984), reported the values of K for commercially available foot valves tested by it, ranging from 1.91 to 5.88. Ram, *et al.* (1982) reported that the values of K ranged from 2.91 to 11.4 for the commercially available samples of foot valves tested at Pantnagar. They also stated that the total area of opening of the three samples of strainers tested were 33, 42 and 107 per cent of the respective areas of opening of their base plates over which their flap valves were to rest. The angles of inclination of the flap valves at full opening were 45°, 55° and 60°. All these deficiencies and inconsistencies resulted in wide variations in K values of commercially available foot valves (Figs. 9.22 to 9.25). High frictional losses result in energy loss and low yield of pumping sets. The Bureau of Indian Standard prescribes that the value of K for foot valves should not exceed 0.8 and K values for reflux valves should not exceed 0.6 (IS : 10805-1986).

Ram *et al.* (1982) evaluated the influence of the ratio of the area of opening of the strainer to the cross-sectional area of the suction pipe. For ratios of 1, 1.5, 2.0, 2.5, 3.0 and 3.5, the values of the coefficient of friction K were 2.12, 1.23, 1.02, 0.82, 0.77 and 0.75, respectively. It was also observed that the shape of the strainer had a significant influence on the value of K. They suggested the following criteria for the design of foot valves in terms of the diameter d of the suction pipes.

1.	Diameter of foot valve casing-cum-strainer	d + 50 mm
2.	Length of the foot valve body	250 mm
3.	Diameter of the opening in the base plate over which the flap valve rests	d mm
4.	Diameter of leather washer of flap valve	d + 25 mm
5.	Diameter of lower plate of flap valve	d – 10 mm
6.	Diameter of upper plate of flap valve	d mm

Figure 9.26 illustrates the construction details of the Pantnagar foot vlave.

9.10.2 Check Valve

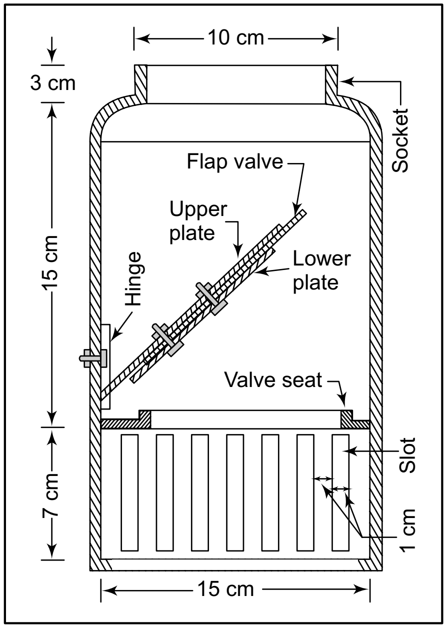


Fig. 9.26 Sectional view of Pantnagar foot valve

In case of shallow tube wells operated by centrifugal pumps, the suction pipe is sometimes lowered into the tube well. In such a case, a check valve is fitted at the bottom of the suction pipe. Its function and design requirements are similar to those of the foot valve. The only difference is that there is no need for a strainer. The check valve permits water to flow in the upward direction but checks the return flow, keeping the pump primed. The flow is controlled by means of a disc rising and falling on a seat with the differential pressure of water. The return of the valve to its seat may sometimes be aided by a spring. The main criteria for selecting a valve is that the cross-sectional area of the seat should not be lower than that of the suction pipe, and the valve should open nearly full to ensure unrestricted flow to the pump.

9.10.3 Reflux Valve

The reflux valve (Figs. 9.27 to 9.29) is fixed on the suction side of the pump. The main purpose of the reflux valve is to retain water in the pump and the suction pipe section between the pump and the reflux valve, to help in priming. The reflux valve is used in case of pumps directly connected to the suction pipe. It is a one-way valve, as in the case of foot valves, opening upward. The water added to the pump for priming remains above the valve. It is also used on the delivery side of the pipeline leading to overhead tanks and long distance conveyance through pipelines. Under such applications, it permits the water to flow in the forward direction only and check the return flow and prevent water hammering.

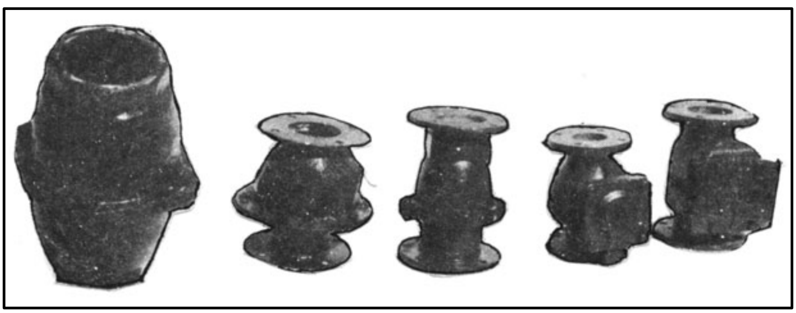


Fig. 9.27(a) A set of commercially available reflux valves used in shallow tube wells. Note that the two valves on the left are not provided with inspection plates

The reflux valve is operated by the pressure differential in the pipeline and has no external means of control. The flow is controlled by means of a disc rising and falling on a seat, with the pressure on the delivery side. The return movement is sometimes aided by a spring. The flow can also be controlled by means of a flap valve swinging up to permit the flow of the delivery pipe, and resting on a seat to prevent return flow. Unlike the foot valve, there is no strainer in a reflux valve since it is used mainly in tube wells.

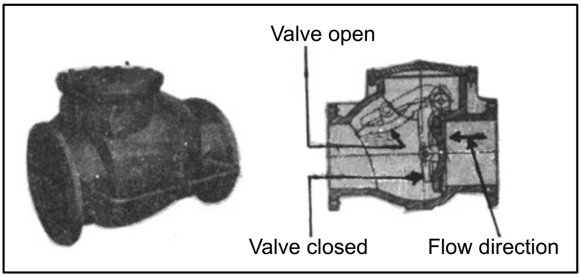


Fig. 9.27(b) A heavy-duty reflux valve provided with a by-pass. A sectional view of the valve showing the rubber lined flap is shown on the right.
Adapted from: Kirloskar Bros. Ltd., Kirloskarvadi, Dist. Sangli

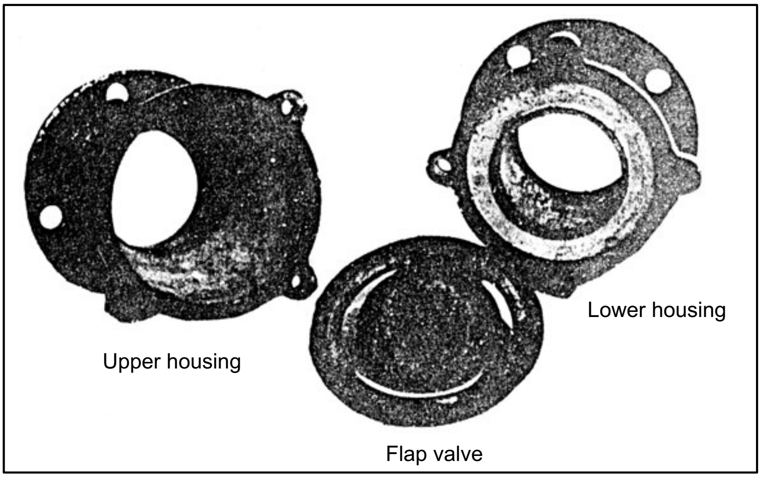


Fig. 9.28 Exploded view of a reflux valve without inspection plate

It has been observed that the reflux valves available in the market vary greatly in standard and quality. Poor quality reflux valves result in excessive head loss due to friction and low efficiency due to restrictions in the flow path of water and inadequate opening. A reflux valve should satisfy the following requirements:

1. The area of opening, where the valve rests, should be equal to or more than the area of the suction pipe.
2. The valve should be so designed that it opens almost fully. It should be leak-proof when closed.

3. Reduction in cross-sectional area of the valve chamber should be smooth and uniform.
4. Projection and size of the inspection plate should be minimum.
5. Flap weight should be such that the minimum of energy loss occurs while lifting.

Kaushal *et al*. (1986) reported that the values of K of commercially available reflux valves ranged from 0.32 to 2.15. It was suggested that a K value of 0.5 should be considered an acceptable maximum. It was observed that a 1 : 1 ratio of the area of opening of the valve plate to that of the corss-section of the suction pipe could be considered optimum. The details of the flap valve of the reflux valve are the same as that of the foot valve.

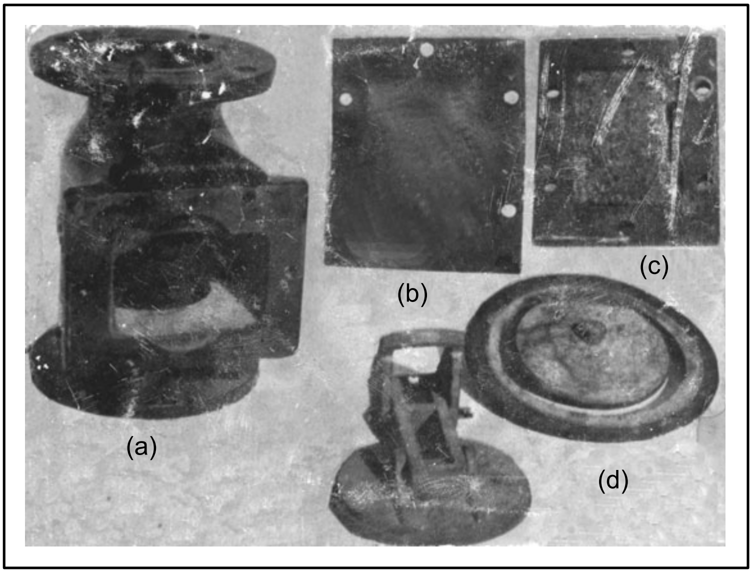


Fig. 9.29 Exploded view of a reflux valve provided with inspection plate: (a) Valve body, (b) Gasket, (c) Inspection plate, (d) Flexible member of flap valve, (e) Flap valve with bottom plate

Location of Reflux Valve with Reference to the Static Water Level

A reflux valve is fixed on the suction side of the pump set and helps prime the pump while starting. It has been observed that the reflux valve is fitted in the suction line, at varying distances with respect to water level. As the distance of the valve above the water surface increases, the number of primings increases because of the increased length of the air column in the suction line. Kaushal *et al.* (1982) observed that the efficiency of a pump set decreased by 10 per cent when the vertical distance between the water level and the reflux valve increased from 10 to 335 cm, the total static suction libt remaining the same. It is recommended that the reflux valve should be located as close to the static water level as possible.

9.10.4 PUMP FITTINGS

The pump fittings used in pump installation include bends, elbows, T-joints and reducers. Each fitting offers a head loss due to friction, resulting in higher input power which adds to the cost per unit of pump discharge. Care should be taken that the number of bends and tees is kept to a minimum. A sharp bend of 90° offers the maximum head loss and, therefore, long radius bends of smooth surface and good quality should be used in pump installation rather than elbows. Similarly, T-joints of good quality should be used to keep the frictional losses to a minimum. The use of reducing sockets should be avoided as far as possible.

9.11 ECONOMICAL PIPE SIZE SELECTION

Before installing a pumping set, it is essential to determine the economical size of the suction and delivery pipes to be connected to the pump. The sizes of these pipes should match with the area of opening of the respective ends on the centrifugal pump. If the pipe size is smaller, it would restrict the discharge capacity of the pump and cause excess loss of pressure in the pipeline due to friction.

The selection of the pipe size of a pumping system should be based on careful economic analysis. A small pipe may require a lower initial investment, but the head loss due to friction would be high. This would increase the power cost. In many cases, a larger pipe will save more in power cost than the additional investment. Further, a larger pipe may reduce the total suction head, thus improving the efficiency of the pump.

EXAMPLE 9.9 A centrifugal pump is required to supply water at a rate of 7.5 1/s through a pipe 300 m long. The combined efficiency of the pump and the motor is 70%. The cost of electricity is 18 paise per kW h. Select the most economical size of pipe commonly available in the market. The prevailing rate of interest on investment may be assumed to be 10 per cent. The pump is to be operated for a total period of 2600 hours in a year.

Solution

1. The possible sizes of pipes from which the selection could be made are assumed to be 5, 6, 7, 8, 10 and 12.5 cm internal diameter.
2. The cost of 300 m of pipe of each size is estimated.
3. The average interest on investment on pipes of each size is computed.
4. The depreciation in the value of the pipe is computed in each category, assuming an average life span of 25 years.
5. The head losses due to friction in the different sizes of pipes are computed.
6. The horse power consumed in overcoming the friction head and the consequent cost of electric power are calculated from the following relationship:
   (i) Cost of energy = Energy consumption × Cost of electrical energy
   (ii) Energy consumed annually, kW h

$$= \frac{\text{Discharge, 1/s} \times \text{Friction head, m} \times 0.746 \times \text{hours of pumping}}{76 \times \text{Overall efficiency}}$$

The results are tabulated below:

Size of pipe (int. (dia.)	Cost of 300 m long pipe (includ-ing ins-tallation)	Interest on in-vest-ment	Deprecia-tion charges @ 4%	Head loss due to friction in 300 m long pipe	Annual con-sump-tion of energy to over-come friction in pipe line	Cost of energy consum-ed in over-coming friction	Total cost per year
cm	Rs	Rs	Rs	m	kW h	Rs	Rs
5	8,760	438.00	350.40	186.0	50,859.8	9154.77	9943.17
6	10,800	540.00	432.00	72.0	19,687.7	3543.79	4515.79
7	13,104	655.20	524.16	31.8	8,695.4	1565.17	2744.53
8	15,126	756.30	605.04	15.6	4,265.7	767.83	2129.17
10	19,200	960.00	768.00	4.5	1,230.5	221.49	1949.49
12.5	24,450	1222.50	978.00	1.41	385.6	69.40	2269.90

It may be seen that the annual operating cost is the lowest in case of a 10 cm pipe. Thus, a pipe of 10 cm diameter is selected.

9.12 SELECTION OF PUMP DRIVE

The mechanical power available at the shaft of an electric motor or engine has to be transmitted to the pump to drive it. This can be done either by direct drive, by means of flexible and fixed couplings, or by indirect drive by means of flat belts, V-belts, chains, gears or a combination of these. The choice of drive depends on the speed of the pump, convenience and space available for installing the engine or motor and the distance between the pump and the prime mover.

Direct drive can be employed where the motor/engine axis can be made to coincide with that of the pump, and where the speed of the pump is the same as that of the motor or the engine. Solid coupling (common shaft) requires accurate alignment; otherwise there is a possibility of broken shafts. Another drawback of a solid coupling is that sudden shocks of the load are transmitted to the motor/engine. In the case of belt drive, the belt slips under sudden loads and the motor/engine is saved from the shock. Flexible couplings overcome both the above defects to some extent. They can accommodate some angular, lateral or vertical misalignment. In this case also care should be taken to ensure that the proper alignment is maintained.

Flat-belt drives are normally satisfactory where the distance between the pully centres exceeds thrice the diameter of the larger pulley. For distances lower than this, V-belt drives are preferred. The maximum belt speed should normally not exceed 1250 m/min. In general, vertical drives should be avoided where flat belts are used. Normally, the pulleys will be crowned to keep the belt running in the centre of the pulleys, but where fast-and-loose pulleys are used, the motor/engine pulley must be of the flat type, the belt being held in place by a fork guide.

Sometimes space does not permit the fitting of V-belt pulleys. Under such situations, it is often advantageous to adopt chain drives. It is possible to have higher speed ratios with chain drives than with other dirves, thus enabling the easy installation of high-speed motors. To determine the speed ratio, the number of teeth on the driven sprocket must be divided by the number of teeth on the driver sprocket. Thus, a speed reduction of 4 to 1 would require four times the number of teeth on the driven sprocket. However, chain drives have limited application in water pumps.

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PROBLEMS

9.1 Determine the annual consumption of electrical energy by a motor driven centrifugal pump installed in a shallow well. The pump discharge is 16 1/s against a total head of 7 m. The pump efficiency is 70% and the motor efficiency is 84%. The drive efficiency may be assumed to be 100%. The pump is operated for 3500 hours per year.

Ans. 6546 kW h

9.2 A volute centrifugal pump installed in a deep open well is driven by a diesel engine, using a two-stage belt drive. The pump discharge is 20 1/s. The suction pipe is 10 cm in diameter and 7 m long. The pumping water level is 5.8 m below the centre line of the pump. The suction pipe is connected to the pump by a long sweep bend of 10 cm inside diameter. A 10 cm diameter foot valve is fixed at the intake of the suction pipe. The static discharge head is 12 m. The discharge pipe is 8 cm in diameter and 16 m long. Three long sweep bends and a reflux valve, each of 8 cm diameter, are fixed on the discharge line. The pump discharges into a pressure tank, the pressure inside which is 0.6 kg/cm^2. Determine (i) the total head, and (ii) brake horse power of the engine if the pump efficiency is 74% and drive efficiency 80%. (iii) If the specific fuel consumption of the diesel engine is 0.23 1/kWh, what is the monthly requirement of diesel to run the engine, if the pump works for 10 hours each day?

Ans. (i) Total head, 34.52 m
(ii) Brake horse power, 15.33
(iii) Monthly diesel requirement, 799.40 *l*

9.3 A pump lift 100,000 1 of water per hour against a total head of 20 m. Compute the water horse power. If the pump has an efficiency of 70 per cent, what size prime mover is required to operate the pump. If a direct-drive electric motor with an efficiency of 80% is used to operate the pump, compute the cost of electrical energy in month of 30 days. The pump is operated for 12 hours daily. The cost of electrical energy is 25 paise per unit.

Ans. (i) Water horse power, 7.31 hp
(ii) Size of motor, 10.44 hp
(iii) Cost of electrical energy, Rs. 876.60

9.4 At its duty point a pump produces 45 m head for a flow of 8 1/s at an efficiency of 54%. At maximum discharge (10.5 1/s) the pump produces 35 m head with an efficiency of 50%. Given the standard electric motors below, select an electric motor for this pump. Standard motor sizes: 3.75, 5.6, 7.5, 9.3, 11.2 kW.

Ans. 7.5 kW

9.5 Determine the pump capacity for an area of 6 hectares of wheat crop based on daily peak evapotranspirarion rate of 6 mm/day, if the pump works for 8 hours each day. Assume effective rainfall as 10% of evapotranspiration rate and overall irrigation efficiency 60%. What will be the pump capacity if the contribution due to shallow water is assumed as 30% of the evapotranspiration rate?

Ans. 18.75 *l*/s; 12.5 *l*/s

SHORT QUESTIONS

I. State True (T) or False (F).

1. In variable displacement pump there is direct relationship between discharge and pressure head.
2. Variable displacement pumps are predominantly used in irrigation.
3. Volute pump is a type of variable displacement pump.
4. In diffuser pumps a series of guide vanes of blades surrounds the impeller.
5. The quantity of water that a centrifugal pump can deliver against a given head is inversely proportional to diameter of inlet eye and width of the impeller.
6. A vertical centrifugal pump has a vertical impeller mounted on a horizontal shaft.
7. A multi-stage pump has two or more impellers on a common shaft.
8. In a multi-stage pump, the head and power requirements increases in direct proportion to the number of stages.

9. In a multi-stage pump, the discharge capacity increases in direct proportion to the number of stages.
10. Open type impeller is more efficient than an enclosed impeller.
11. Gun metal impellers are used to handle brackish or salt water.
12. The suction lift of horizontal centrifugal pump is limited to about 6.5 m.
13. Belt driven pump is provided with a pulley head.
14. Suction lift exists if the free water surface of the source of water supply is above the centre line of the pump.
15. In double suction pumps the impellers are cast back to back.
16. Centrifugal pump is not compatible with highly viscous liquid.
17. When water is forced to go faster in a pipe, the pressure in the pipe increases.
18. When the source of water supply is above the centre line of the pump, the total head is the sum of delivery head and velocity head minus the total suction head.
19. Cavitation is accompanied by reduction in efficiency of the pump.
20. Cavitation occurs when the hydraulic head at pump inlet is too high.
21. Suction head is negative pressure head.
22. Net positive suction head is not a characteristic of centrifugal pump.
23. The centrifugal pump works on the principle of partial conversion of velocity head in to pressure head.
24. Vapour pressure has a limiting effect on the suction lift.
25. Water horse power is always greater than brake horse power.
26. In monoblock pumps, the drive efficiency is 100 per cent.
27. In direct-driven pumps, the brake horse power is not equal to shaft horse power.
28. Knowledge of pump characteristics enables the selection of most efficient pump for specific operating conditions.
29. In centrifugal pump, as the discharge increases, the head decreases.
30. The efficiency of a pump is zero for zero discharge.
31. The speed of the pump has no influence on the nature of characteristic curve.
32. For successful operation of a centrifugal pump, the net positive suction head available must be less than the net positive suction head required.
33. Two pumps are connected in series to produce more discharge.
34. Two pumps are connected in parallel to produce more head.
35. The system head curve is time dependent.
36. The pump should be selected according to safe yield of the well.
37. While selecting a multi-stage pump, the pump with steeper head capacity curve should be selected.
38. V-belt drive should be preferred where the distance between the pulleys centre exceeds thrice the diameter of the larger pulley.
39. The flow through the impeller of a horizontal centrifugal pump is parallel to axis of drive shaft.
40. Variable displacement pumps require least input of power at low heads.
41. Variable displacement pumps use a rotating impeller to pump water.
42. A given pump with a given impeller diameter and speed will raise a liquid to a certain height regardless of the weight of the liquid.

43. A given pump with a given impeller diameter and speed will develop same pressure regardless of the weight of the liquid.
44. The centrifugal pump can pump only liquids not vapors.
45. The centrifugal pump is efficient at low heads.
46. The NPSHR is a function of system design.
47. The NPSHA is a function of pump design.
48. The affinity laws are valid only under conditions of constant efficiency.
49. The radial flow impellers are high flow low head designs.
50. A reflux valve is a non-return valve.
51. The system head curve gives the relationship between the discharge and the total suction lift in a pumping system.
52. When the speed of a centrifugal pump is changed, the head varies as the cube of the speed.
53. A pump will deliver the normal amount of water when the impeller is worn.
54. The foot valve is an integral component of centrifugal pump installed to lift water from open wells.
55. The foot valve and reflux valve are used on suction side of the pump.
Ans. True: 2, 3, 4, 7, 8, 11, 12, 13, 15, 16, 18, 19, 21, 23, 24, 26, 28, 29, 30, 35, 36, 37, 41, 42, 44, 48, 50, 54, 55.

II. Select the correct answers.

1. When the speed of a centrifugal pump is changed, the head varies as
(a) the speed (b) square of the speed
(c) square root of the speed (d) cube of the speed
2. Theoretically centrifugal pump can lift water from a maximum depth of
(a) 8.33 m (b) 9.33 m
(c) 10.33 m (d) 11.33 m
3. When the speed of a centrifugal pump is changed, discharge
(a) remains constant (b) varies directly as speed
(c) varies as the square of the speed (d) varies as the cube of the speed
4. For a given type of impeller, the head and power requirements of multistage centrifgual pump increases in
(a) direct propotion to the number of stages
(b) are almost same as for single stage of the pump operating alone
(c) varies as square of stages
(d) varies as cube of the speed
5. The commonly used centrifugal pump impeller to pump brackish or salt water is made of
(a) bronze (b) cast iron
(c) gun metal (d) brass
6. One of the factors to be considered in the selection of a suitable centrifugal pumping set is
(a) the total head on the pump (b) total depth of the well
(c) type of aquifer (d) finished inside diameter of the well
7. In centrifugal pump liquid enters through
(a) impeller vane (b) eye of impeller
(c) stuffing box (d) diffuser

8. In turbine pump, the impeller is surrounded by
   (a) diffuser vanes (b) volute casing
   (c) cylinder (d) plunger
9. In semi-open impeller, vanes are
   (a) provided with side walls on either side
   (b) attached to a central hub
   (c) provided with side wall at the back
   (d) provided with shrouds on either side
10. In centrifugal pump, the cavitation is accompanied by
    (a) increase in efficiency of the pump (b) increase in pressure inside the pump
    (c) decrease in efficiency of the pump (d) chemical destruction of metal
11. The combined head of two pumps operating in a series for a specific discharge is equal to
    (a) individual head (b) sum of individual head
    (c) square of sum of individual heads (d) cube of sum of individual heads
12. The combined discharge of two pumps operating in parallel for a specific head is equal to
    (a) sum of individual discharges
    (b) individual discharge
    (c) square of sum of individual discharges
    (d) cube of sum of individual discharges
13. The most suitable irrigation pump to lift water from stream/canal with lift less than 2.5 m is
    (a) jet pump (b) submersible pump
    (c) centrifugal pump (d) propeller pump
14. The most suitable derive, where the distance between the pump and the prime mover exceeds thrice the diameter of the larger pulley is
    (a) v-belt (b) chain
    (c) gear (d) flat belt
15. Foot valve is fitted at
    (a) junction of delivery pipe and pump body
    (b) junction of suction pipe and pump body
    (c) end of suction pipe
    (d) end of delivery pipe
16. The system head curve of a pump indicates the
    (a) friction loss of the system (b) liquid velocity in the system
    (c) total head required by the system (d) brake horse power of the motor
17. A double suction pump is a type of ________ pump.
    (a) centrifugal (b) reciprocating
    (c) piston (d) submersible
18. Stages are added to centrifugal pumps to increase
    (a) motor horse power
    (b) efficiency of the impeller
    (c) the total head that pump can produce
    (d) vacuum pressure

19. If the speed of a centrifugal pump is increased, and the head remains the same, the litres per second output will
    (a) increase slightly, then decrease (b) increase
    (c) decrease (d) remains the same
20. To prevent the pumped liquid from leaking along the shaft, pumps include
    (a) bearings (b) packing or mechanical seals
    (c) shaft sleeves (d) volutes
21. To save space and cost, some pumps are built onto the motor shaft, these are called
    (a) monoblock (b) diffuser type
    (c) vertical in line (d) directly coupled
22. If the RPM of a pump are increased by 50 per cent, the required BHP will increase by
    (a) 50 per cent (b) 1.75 times
    (c) 2.25 times (d) 3.38 times
23. One kilowatt is equal to
    (a) 0.746 HP (b) 1 HP
    (c) 1.34 HP (d) 1.50 HP
24. The positive displacement type pump includes
    (a) axial flow and centrifugal (b) axial flow and rotary
    (c) reciprocating and rotary (d) centrifugal and rotary
25. Check valves are used to
    (a) stop flow in both directions (b) permit flow only in one direction
    (c) permit air to escape from the pipe (d) regulate velocity

Ans. 1 (b) 2 (c) 3 (b) 4 (a) 5 (c) 6 (a) 7 (b) 8 (a)
9 (c) 10 (c) 11 (b) 12 (a) 13 (d) 14 (d) 15 (c) 16 (c)
17 (a) 18 (c) 19 (b) 20 (b) 21 (a) 22 (d) 23 (c) 24 (c)
25 (b)

10

Centrifugal Pumps: Design, Installation, Operation, Maintenance and Troubleshooting

Centrifugal pumps have two basic groups of parts, rotating and stationary. Rotating parts include the impeller, shaft, wearing rings, shaft sleeves, bearings and mechanical seals. Stationary parts include the casing, bearing housing, foot valves/reflux valves, strainer, pipes and pipe-line accessories. Each component should be designed to obtain adequate operational efficiency.

10.1 DESIGN OF CENTRIFUGAL PUMPS

10.1.1 Basic Hydraulics

The principles of fluid flow applicable to centrifugal pumps include Bernoulli's equation, velocity triangles, specific speed, total head and computation of losses due to disc leakage, friction and other mechanical losses.

10.1.2 Bernoulli's Equation for Stationary Conduits

Assuming no loss in flow, the total head H is the same for any point along a stream line (Fig. 10.1)

$$H = \frac{P}{\gamma} + \frac{v^2}{2g} + Z \qquad (10.1)$$

where, H = total head, m

P/γ = static pressure head, m

$v^2/2g$ = velocity head, m

Z = elevation head, m

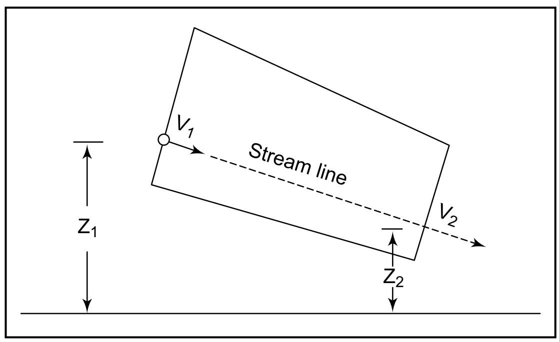

Fig. 10.1 Definition sketch of Bernoulli's equation

However, in actual practice, the head does not remain constant because of friction and turbulence losses. Hence, Eq. (10.1) can be written as follows:

$$H = \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + Z_2 + \text{Losses between points 1 and 2} \tag{10.2}$$

If the cross-sectional area of a horizontal pipe is increased gradually, the velocity will be decreased. Since the potential head remains constant, if the pipe is horizontal, the decrease in velocity results in an increase in pressure head.

Velocity Triangles

The velocity of a fluid element could be represented by a vector. The length of the vector gives the magnitude of the velocity. The direction of the vector is tangential to the stream line. In case of a centrifugal pump, the impeller is rotating, while its casing is stationary. The fluid velocity in an impeller channel can be represented by either the absolute velocity or the relative velocity. The relative velocity of flow is considered relative to the impeller, while the absolute velocity of flow is taken with respect to the pump casing and is always equal to the vector sum of the relative velocity and the peripheral velocity of the impeller. The peripheral velocity is given by

$$u = \frac{\pi Dn}{100} \tag{10.3}$$

Where, u = peripheral velocity, m/s

D = impeller diameter, cm

n = speed of impeller, rpm

A study of the components of flow through an impeller is best carried out graphically by means of velocity vectors. The velocity vector diagram is triangular and it is called a velocity triangle. It can be drawn for any point of the flow path through the impeller. However, velocity triangles are usually drawn on the entrance and discharge ends of the impeller vanes. Hence, velocity triangles are called entrance and discharge triangles.

The entrance and discharge velocity diagrams of an impeller with backward curved vanes, considering that no circulatory flow takes place, are shown in Fig. 10.2. Idealized velocity triangles (Fig. 10.3) are drawn by assuming perfect guidance of flow by vanes.

The following notations are used:

u = peripheral velocity of impeller, m/s
ω = relative velocity of flow, m/s
C = absolute velocity of flow, m/s
C_m = radial component of absolute velocity of flow, m/s
C_u = tangential component of absolute velocity of flow ($C \cos \alpha$), m/s
α = angle between C and u, degrees
β = angle between ω and u (extended) degrees

The angle β is the angle made by a tangent to the impeller vane with a line in the direction of motion of the vane. Subscripts 1 and 2, Figs. 10.3 (a) and (b), refer to the entrance and discharge points, respectively. The tangential components of relative and absolute velocities are given by the subscript u. Components normal to the peripheral velocity are denoted by C_{m1} and C_{m2}, for entrance and discharge velocity diagrams, respectively. This component is radial in a radial impeller and axial in an axial impeller.

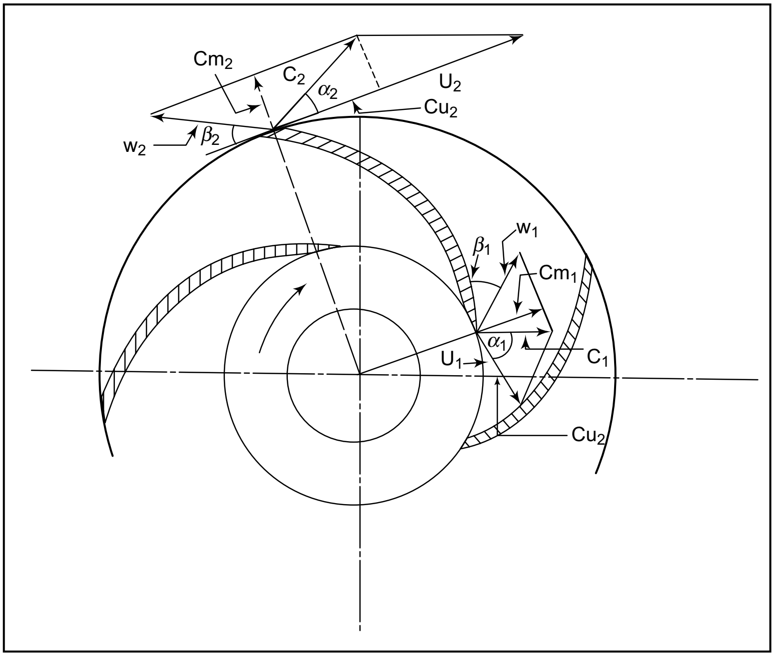

Fig. 10.2 Entrance and discharge velocity diagrams of an impeller with backward curved vanes

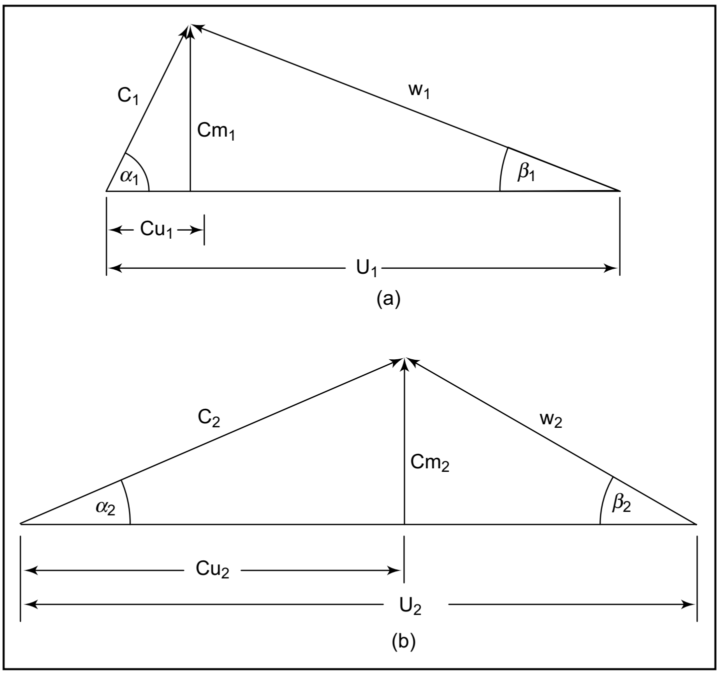

Fig. 10.3 Virtual entrance and discharge velocity triangles of the impeller shown in Fig. 10.2

In actual practice, however, circulatory flow takes place. When the impeller is rotated and the water is pumped out, the water tends to rotate or circulate in a direction opposite to the direction of rotation of the impeller. Therefore, in a rotating impeller, two flows take place simultaneously, the flow of fluid through the passage plus the circulatory flow. The direction of circulatory flow is opposite to the rotation of impeller, at the rim, and in the same direction at the hub.

The circulatory flow decreases the absolute velocity at the outlet from C_2 to C'_2, and increases the absolute velocity at the inlet from C_1 to C'_1. The circulatory flow also influences the vane angle and the absolute angles. The vane angle β_2 is decreased while the absolute angle α_2, at which the fluid leaves the wheel, is increased. In case of inlet, β_1 is increased, while absolute angle α_1 is decreased. The flow and the outlet area remain the same. Thus, the average radial components of absolute velocities remain unchanged.

As indicated above, the actual relative velocity w' and the actual absolute velocity c' are different from the idealized velocities. The effect of circulatory flow on the entrance and discharge velocity triangles is shown in Fig. 10.4. The virtual (idealized) diagrams are shown dotted. The effect of circulatory flow on the entrance diagram is substantially low because the vanes are close together.

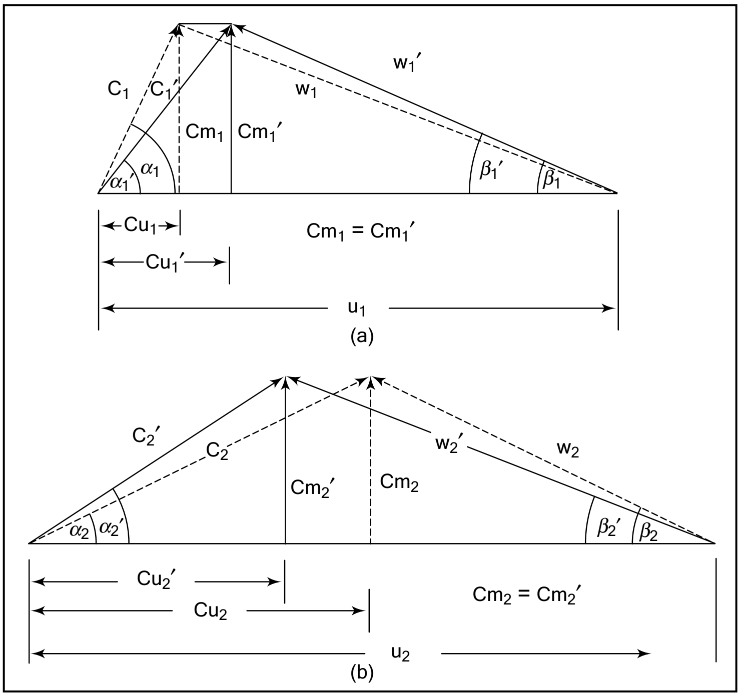

Fig. 10.4 Entrance and discharge velocity triangles with circulatory flow corrections. The dotted lines show the virtual triangles

The effect of circulatory flow is explained through a correction factor, which is defined as

$$\eta_\infty = \frac{Cu_2'}{Cu_2} \tag{10.4}$$

It is assumed that the correction factor is a function of the number of vanes, the vane discharge angle and, sometimes, the impeller radius ratio r_2/r_1. The correction factor can be determined by using a formula given by Stodola (1945), as follows:

$$\eta_\infty = 1 - \frac{\pi \sin \beta_2}{Z} \tag{10.5}$$

where, Z = number of vanes

However Eq. (10.5) gives slightly higher values.

Pfleiderer (1955) gave the following values for the correction factor, depending upon the number of vanes:

Z	1	2	4	6	10	20	∞
η_∞	0.25	0.40	0.572	0.666	0.77	0.87	1.0

Leakage Losses

Leakage loss is defined as the loss of capacity of the pump through the running clearance between the rotating element and the stationary casing. It can take place at the following places:

1. Between the casing and the impeller (at the impeller eye)
2. Through the stuffing box
3. Through the axial thrust balancing devices
4. Through the bushing, when used to reduce the pressure on the stuffing box

Mathematically, leakage loss can be expressed in terms of volumetric efficiency.

$$\text{Volumetric efficiency, } \eta_v = \frac{Q}{Q + Q_L} \tag{10.6}$$

where, Q = discharge, m^3/s

Q_L = rate of leakage, m^3/s

Disc Friction Losses

The outer surface of a rotating impeller is subject to friction from the surrounding fluid. The power required to rotate a disc (impeller) in a fluid is known as the disc friction loss. Usually, the impeller will have enclosed sides which rotate in the fluid, the required power being supplied by the driver. The power loss due to friction may be determined by Pfleiderer's equation (Pfleiderer, 1955).

$$h_{pDF} = 10^{-6} \gamma u_2^3 D_2^2 \tag{10.7}$$

where, $h_{p\,DF}$ = power loss due to disc friction loss, h_p

u_2 = rim velocity, m/s

D_2 = rim diameter, m

γ = specific weight of liquid, kg/m^3

However, Eq. (10.7) gives higher values for high peripheral speeds.

Gibson (1934) gave the following relationship to estimate disc friction loss:

$$h_{pDF} = \frac{(D_2)^{4.83} n^{2.83}}{2.78\,(10)^6} \tag{10.8}$$

where, n = speed, rpm

D_2 = rim diameter, m

Mechanical Losses

Mechanical losses include the frictional losses in the bearings and stuffing boxes. The frictional losses in the stuffing box are influenced by a number of factors, such as pump speed, pressure, method of packing and lubrication. Friction losses in the bearing vary, for the same size and load, for different makes of bearings. Therefore, the mechanical losses can be calculated precisely only when the design details of bearings and seals are available. However, these losses vary from 2 to 4 per cent.

$$\eta_m = \frac{\text{Brake horse power} - \text{Mechanical losses}}{\text{Brake horse power}}$$

Overall Head Coefficient

The pressure head developed by a body of fluid rotating in a closed vessel is expressed as follows:

$$H = \frac{u_2^2}{2g}$$

or $$u_2 = \sqrt{2g\,H}$$

However, under actual shut-off conditions, this value is not obtained. So, a factor ϕ is introduced in the above equation.

$$u_2 = \phi\,\sqrt{2g\,H} \tag{10.9}$$

The value of ϕ is usually close to unity.

Equation (10.9) may also be used to determine the required outside impeller diameter, if H is the head corresponding to the point of best efficiency and ϕ is the corresponding coefficient

$$u_2 = \frac{\pi D_2 n}{60} = \phi\sqrt{2g}\,\sqrt{H} \tag{10.10}$$

∴ $$D_2 = \frac{60}{\pi}\phi\sqrt{2g}\,\frac{\sqrt{H}}{n}$$

$$= \frac{84.5\,\phi\,\sqrt{H}}{n} \tag{10.11}$$

The value of ϕ varies from 0.9 to 1.20, with an average value of unity. With a view to avoiding any doubt concerning the correct value of ϕ to be assumed, it is always advisable to use a higher value which results in a larger outside diameter of the impeller. This will make certain that sufficient head is obtained. In the absence of the above reference, a value of 1.05 may be adopted.

Specific Speed

The earlier practice was to classify pumps according to their hydraulic type ratio, such as ratio of the impeller eye diameter to the impeller outside diameter (D_1/D_2), or ratio of the impeller width at the discharge end to the outside diameter of the impeller (b_2/D_2). Modern pumps are characterized by specific speed, which is defined as

$$n_s = \frac{n\sqrt{Q}}{H^{3/4}} \tag{10.12}$$

where, n = pump speed, rpm

Q = pump capacity, m^3/s

H = total head against which the pump is to be operated, m

The specific speed is calculated for a given capacity and head. For a multi-stage pump, the specific speed is calculated on the basis of the head per stage. In case of a double suction pump, the specific speed is calculated on the basis of one half the capacity.

10.1.3 Design of Impeller

The design of a pump impeller involves the following steps:

To meet a given head and capacity, the speed of rotation of the impeller is selected first. This establishes the specific speed. Usually the pump speed selected corresponds to the standard speed of electric motors, such as 1440 rpm or 2900 rpm, with 50 cycles/s frequency of alternating current (AC). The efficiency of a pump is a function of its specific speed and capacity. Wislicenus (1947) published a plot (Fig. 10.5) of the *approximate statistical averages,* of the efficiencies of a large number of commercial centrifugal pumps, versus specific, which may be used as a yardstick to assume the efficiency for a given set of conditions.

With the help of the calculated specific speed and a given capacity, the attainable efficiency of the proposed impeller may be predicated. The impeller profile and the layout of the vanes may be done if the following elements of an impeller are known.

1. Meridional or radial velocities at the inlet and outlet
2. Outside diameter of the impeller
3. Impeller vane inlet and outlet angles

With the help of the above data, Euler's entrance and discharge velocity triangles may be drawn, as shown in Figs. 10.3 (a) and (b). Single-curvature or plain-curvature vanes will have to be used for radial-type impeller, and double-curvature vanes for mixed-flow and axial-flow impellers. For straight radial vanes, since all the particles of the fluid enter and leave the impeller at the same diameter, only one entrance and discharge triangle would determine the shape of the vane. In case of mixed and axial flow impellers, the velocity triangles are to be drawn for several stream lines.

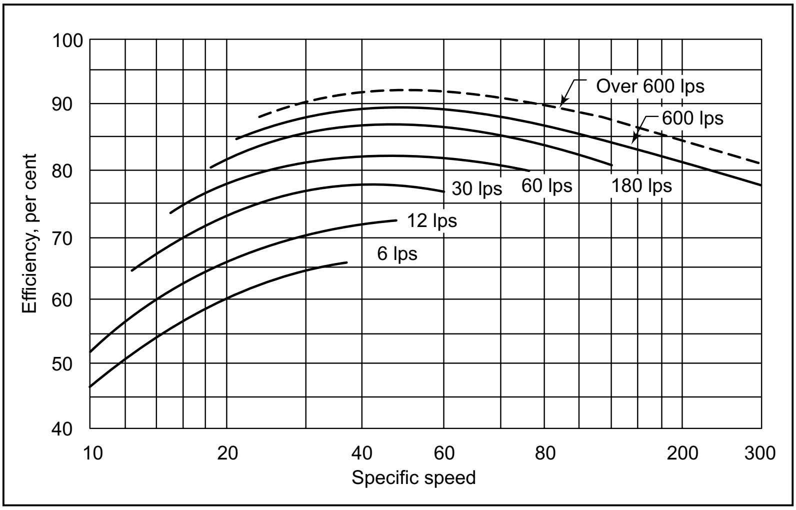

Fig. 10.5 Relationship between specific speed, discharge and efficiency of centrifugal pumps
Based on Wislicenus (1947)

The vane angle (β_2) is one of the most important elements in the design of the pump impeller. For a normal design, β_2 varies from 17.5° to 27.5°. The definition sketch for determining the dimensions of different components of an impeller is shown in Fig. 10.6.

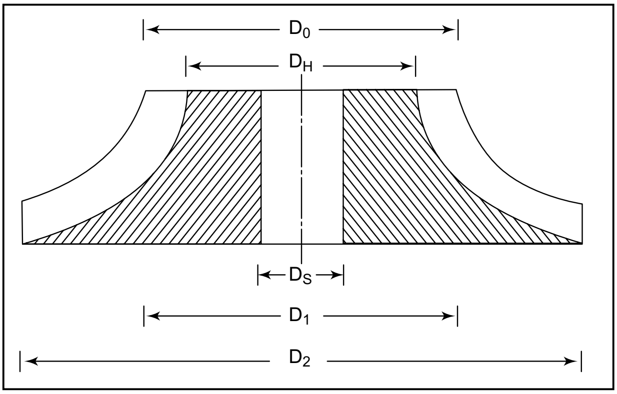

Fig. 10.6 Definition sketch for determining the dimensions of different components of an impeller

The design of the impeller involves the following steps:

Shaft Diameter, D_s

Before fixing the dimensions of the impeller, the shaft size must be approximated. The shaft should be designed to bear the torque and bending moment to avoid excessive lateral deflection. The shaft size, based on torque alone, is given by the following relationship:

$$T_s = \frac{\pi D_s^3 \times f_s}{16} \tag{10.13}$$

or

$$D_s = \sqrt[3]{\frac{16\,T_s}{\pi\,(f_s)}} \tag{10.14}$$

where,
D_s = shaft diameter, m
f_s = allowable shear stress, kg/m^2
T_s = shaft torque, kg-m

T_s is the torque based on the brake horse power (bhp), and is defined as

$$T_s = \frac{4500 \times \text{bhp}}{2\pi \times n} = \frac{715\ \text{bhp}}{n} \tag{10.15}$$

There will be a bending moment due to the impeller and shaft weights and unbalanced radial thrust acting on the impeller. Based on the bending moment, the shaft diameter can be determined by the following relationship:

$$D_s = \sqrt[3]{\frac{32\,M}{\pi\, f_t}} \tag{10.16}$$

where,
M = maximum bending moment, kg-m
f_t = allowable tensile or bending stress, kg/cm^2

The maximum combined shear stress f'_s, due to the bending stress f_t and torsion stress f_s, is given by

$$f'_s = \frac{1}{2}\sqrt{4f_s^2 + f_t^2} \tag{10.17}$$

The maximum combined tensile stress f'_t is given by

$$f'_t = \frac{1}{2} f_t + \frac{1}{2}\sqrt{4f_s^2 + f_t^2} \tag{10.18}$$

Since accurate checks on the stresses and deflection can be made only after the impeller is designed and the loads are known, at the preliminary stage, the shaft diameter may be based upon shear and bending alone, adopting low allowable stresses to take care of the uncertainties in the load. The diameter of the hub, D_H, is made about 1 cm more than the diameter of the shaft.

Impeller Inlet Dimensions and Vane Angles

The impeller inlet dimensions include the diameter of the suction flange D_{su}, diameter of the eye of impeller, inlet vane edge diameter and width of the impeller at inlet.

Diameter of the Suction Flange, D_{su}

The diameter of suction flange depends upon the diameter of suction pipe, which is determined according to the desired velocity of flow. Its average value is usually 3 m/s. The diameter of the suction flange is determined as follows:

$$D_{su} = \sqrt{\frac{4\,Q}{\pi\,V_{su}}} \tag{10.19}$$

where, D_{su} = diameter of the suction flange, m

Q = pump discharge, m^3/s

V_{su} = velocity of flow at the suction flange, m/s

Diameter of the Eye of Impeller

The inlet velocity through the eye of the impeller C_0 is usually slightly more than the velocity in the suction flange. Its value may vary from 3 to 4 m/s. However, the inlet velocity should be kept on the lower side so as to reduce the turbulence and friction losses. The diameter of the eye of the impeller is determined from the continuity equation, after determining or assuming the values of D_H and C_0, as follows:

$$\frac{\pi}{4} D_0^2 - \frac{\pi}{4} D_H^2 = \frac{Q'}{C_0}$$

$$D_0 = \sqrt{\frac{4}{\pi}\frac{Q'}{C_0} + D_H^2} \tag{10.20}$$

where, Q' is the impeller capacity, m^3/s (including leakage losses which range from 2 to 4 per cent of the delivered flow Q).

Inlet Vane Edge Diameter

The inlet vane edge diameter D_1 is usually assumed to be the same as the diameter of the eye of the impeller, in order to ensure smooth flow without excessive turbulence. In case of a sloping inlet edge, the average value of the diameter may be made equal to the eye diameter, D_0.

Passage Width at Inlet

The velocity of flow at the inlet, C_{m1}, for the design discharge, is radial and recommended to be 5 to 10 per cent higher than the velocity at the impeller eye because speeding up fluid is always more efficient than slowing it up. Using the continuity equation, the width of the impeller at the inlet b_1 is determined from the assumed values of C_{m1} and D_1

$$b_1 = \frac{Q}{\pi D_1 C_{m1} \in_1} \tag{10.21}$$

where, $\in_1$ is a contraction factor, having a value less than 1. This factor is introduced in the equation because the gross inlet area $\pi D_1 b_1$ is not fully available to the fluid, but is reduced due to vane thickness. While calculating the width, the value of $\in_1$ may be assumed to be 0.85. However, the exact value of $\in_1$ can be determined when the number of vanes and their inlet thicknesses are known.

Inlet Vane Angles

The fluid is usually assumed to enter the vane radially. Hence, α_1 is 90°. After determining C_{m1} and u_1, the vane inlet angle β_1 is determined from

$$\tan \beta_1 = \frac{C_{m1}}{u_1} \tag{10.22}$$

The value of β_1 so calculated is generally inereased slightly with a view to taking care of the contraction of the stream, as it passes the inlet edge, and the pre-rotation of the water. Its value generally varies from 10° to 25°.

Impeller Outlet Dimensions and Vane Angle

The outlet dimensions and vane angle of an impeller will include the impeller outlet diameter, width of impeller at outlet and outlet vane angle.

Outlet Diameter, D_2

The outlet diameter can be determined, using Eq. 10.11, which gives the following relationship:

$$D_2 = \frac{84.5\,\phi\,\sqrt{H}}{n} \tag{10.23}$$

where, ϕ is the head coefficient. The value of ϕ depends upon the pump capacity and the total head. Its value may be adopted as discussed in Sec. 10.1.1.

Outlet Vane Angle

The outlet vane angle β_2 may be selected within a fairly wide limit. Usually, its value varies from 15° to 40°. With a view to attaining a smooth and continuous passage, β_2 is assumed to be larger than the inlet angle β_1.

Outlet Passage Width, b_2

While calculating the outlet passage width, the radial outlet velocity C_{m2} is assumed to be the same as or slightly less (10–15 per cent) than the radial inlet velocity C_{m1}. The net area required,

$$A_2 = \frac{Q}{C_{m2}}$$

The gross outlet area is increased to account for the vane thickness. A contraction factor $\in_2$ is assumed to compensate for the vane thickness at the outlet, while calculating the passage width. The passage width, so determined may be corrected later on, if required, when the exact number of vanes are known. The approximate outlet width is given by the following relationship:

$$b_2 = \frac{Q}{C_{m2} D_2\, \pi \in_2} \tag{10.24}$$

The value of $\in_2$ usually varies from 0.90 and 0.95.

Outlet Velocity Diagram

The peripheral velocity u_2 is calculated as follows:

$$u_2 = \frac{\pi D_2 n}{60} \tag{10.25}$$

The virtual tangential component Cu_2 of the absolute outlet velocity C_2 is

$$Cu_2 = u_2 - \frac{C_{m2}}{\tan \beta_2} \tag{10.26}$$

The actual tangential component Cu'_2 of the absolute outlet velocity C_2 is obtained from Eq. (10.4)

$$Cu'_2 = Cu_2 \times \eta_\infty$$

The tangent of the actual outlet angle α'_2 is obtained from the relationship

$$\tan \alpha'_2 = \frac{C_{m2}}{Cu'_2} \tag{10.27}$$

The actual absolute outlet velocity $C'_2 = \sqrt{C_{m2}^2 + C'^2_{u2}}$ (10.28)

Design of Impeller Vanes

After the vane angles and diameter have been determined, the next step is to determine the number of vanes, their curvature and thickness.

Number of Vanes

The number of vanes should be sufficient to secure proper guidance to water. It is also to be noted that too many vanes will result in excessive friction losses. Stapanoff (1992) suggested the following thumb rule to fix the number of vanes

$$Z = \frac{\beta_2}{3} \tag{10.29}$$

where, Z = number of vanes, dimensionless

β_2 = vane angle at the outlet, degrees

Pfleiderer (1955) suggested the following relationship to determine the number of vanes:

$$Z = 6.5 \frac{D_2 + D_1}{D_2 - D_1} \sin\left(\frac{\beta_1 + \beta_2}{2}\right) \tag{10.30}$$

It may be noted that large vane angles require more number of vanes to provide for proper guidance to the liquid. The number of vanes generally recommended for low to medium specific speed pumps varies from 5 to 12.

Vane Curvature

Church and Lal (1973) suggested two methods for the construction of the vane shape, using the vane angle curve plotted between the inlet and outlet radii of the impeller. The methods are (i) tangent arc method, and (ii) polar coordinate method. The first method, which is more common, is discussed in this text.

Tangent Arc Method

The impeller is arbitrarily divided into a number of concentric rings, between radii, r_1 and r_2. The radius of curvature, defining the vane shape between any two rings having radii r_b and r_a, is obtained from the following relationship:

$$\rho = \frac{r_b^2 - r_a^2}{2(r_b \cos \beta_b - r_a \cos \beta_a)} \tag{10.31}$$

The value of ρ is calculated for various rings and plotted according to the procedure given in Example 10.2, to establish the vane shape.

The solution of Eq. 10.31 will require the values corresponding to the radii of concentric rings. The following procedure is used to determine the value of β:

The radial components C_{m1} and C_{m2} of absolute velocity, and vane angles β_1 and β_2 at the inlet and outlet ends are known. The relative velocities w_1 and w_2 at the inlet and outlet ends are calculated from the relationship.

$$\sin \beta = \frac{C_m}{w}$$

The radial velocities C_{m1} and C_{m2} and relative velocities w_1 and w_2 are plotted separately against r_1 and r_2. The end points are joined by a straight line or curve. The intermediate values (between the inlet and outlet ends) for the radial velocity as well as relative velocities corresponding to different radii of concentric rings are determined from the above plots. The vane angles β_1 and β_2 at the inlet and outlet ends are known. The intermediate points are calculated based on the intermediate values of radial velocity and relative velocities, corresponding to different radii. The values of β_1, β_2 and intermediate values of vane angles, so calculated, are plotted against the radius. The values of β corresponding to different rings are from this plot.

After establishing the value of β, corresponding to the concentric rings determined, the radius of curvature ρ of the arcs can be calculated, using Eq. (10.31).

Vane Thickness

The vane thickness, t, in case of a closed impeller having shrouds on both sides, can be determined by assuming the vane to be a beam fixed at the ends and loaded uniformly. However, the thickness so calculated is usually less than the minimum thickness recommended. The minimum thickness of the vane, at the end, usually recommended is 3 mm. The vanes may be of uniform thickness throughout or the thickness may be progressively increased from inlet to outlet.

Passage Width

The passage width at the inlet and outlet ends, which are determined as per the above procedure, are approximate since the number of vanes are not known and arbitary values for the contraction factors,

$\in_1$ and $\in_2$, adopted are in the initial phase of computation. The exact width is determined, adopting a suitable value for the contraction factor $\in$. The contraction factor at any radius can be calculated by using the following relationship:

$$\in = \frac{\pi D - \dfrac{Zt}{\sin\beta}}{\pi D} \tag{10.32}$$

where, D = impeller diameter, m

β = vane angle, degrees

t = thickness of impeller, cm

The width of the impeller passage b is obtained from the following relationship:

$$b = \frac{Q}{\pi D \in C_m} \tag{10.33}$$

where, b = width of the impeller passage at any point, m

Q = pump capacity, m^3/s

D = diameter of the impeller at any point between the inlet and the outlet, m

C_m = radial component of absolute velocity, m/s

$\in$ = contraction factor, dimensionless

The values, of C_m and β at different radii are obtained by the procedure explained for determining the vane curvature.

10.1.4 Design of Volute

Most single-stage centrifugal pumps, except vertical pumps (vertical turbine and submersible pumps), are usually of the volute type. Though a casing with diffuser vanes is more efficient, the volute-type casing is adopted because of its simplicity.

The volute consists of a casing surrounding the impeller. The cross-sectional area of the volute increases gradually from the tongue to the throat (Fig. 10.7). There are several design elements of the volute casing, namely, volute area, tongue angle and discharge flange.

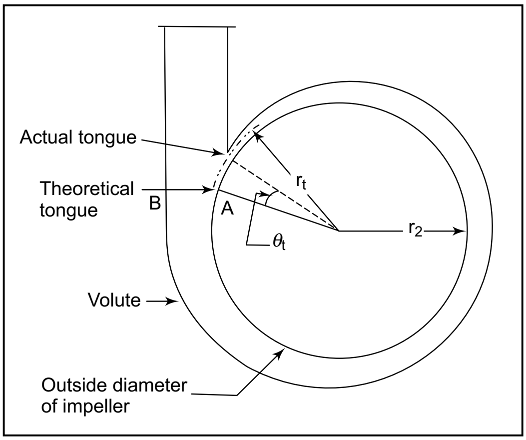

Fig. 10.7 Definition sketch of volute

Volute Area

Referring to Fig. 10.7, the volute area gradually increases from tongue A to throat AB, to accommodate the discharge along the impeller periphery so that the velocity of water in the casing will not increase.

The cross-sectional area is gradually increased to take care of the gradual increase in discharge along the periphery of the impeller.

Assuming that the flow from the impeller is uniform about its periphery, the flow past any section of the volute is $\theta/360$ of the total flow, while θ is the angle measured from the theoretical tongue of the fluid (Fig. 10.7). The angle θ is obtained from the following relationship (Church and Lal, 1973)

$$\theta^0 = \frac{360\, r_2 Cu_2'}{Q} \int_{r_2}^{r_\theta} b \frac{dr}{r} \tag{10.34}$$

where, θ^0 = angle measured from the theoretical tongue, degrees

r_2 = outer radius of the impeller, m

r_θ = radius at an angle θ from the theoretical tongue, m

b = width of the volute at any point, m

The average width of each ring b is obtained as follows (Church and Lal, 1973):

$$b = b_3 + 2\, x \tan \theta^\circ /2 \tag{10.35}$$

where, x = distance between any radius r and outside radius of the impeller r_2, m

θ = maximum total angle between the sides of a volute, degrees (usually the value is 60°)

b_3 = base width, m

= b_2 + Twice the shroud thickness + Clearance on each side of the impeller

The thumb rule for determination of base width b_3 (Lal and Datta, 1971) is to have $b_3 = 2b_2$ for low specific speed, $b_3 = 1.75\, b_2$ for medium specific speed, and $b_3 = 1.62\, b_2$ for high specific speed.

The solution of Eq. (10.34), resulting in average width and area of the volute at various values of θ (0 to 360°), can be computed and compiled in tabular form by the procedure adopted in Example 10.3.

Tongue Angle

The theoretical tongue starts outside the radius of the impeller (Fig. 10.7). However, to avoid turbulance, the actual tongue starts at a radius of r_t which is 5 to 10 per cent greater than the outside radius of the impeller. The tongue angle is obtained from the following equation (Church and Lal, 1973);

$$\theta^\circ = \frac{132 \log_{10} \dfrac{r_t}{r_2}}{\tan \alpha_2'} \tag{10.36}$$

Discharge Flange

The diameter of the discharge flange is generally based upon the average liquid velocity of 5.5 to 7.5 m/s at the design point.

Example 10.1 Determine the inlet and outlet dimensions and angles of a double-suction radial impeller, for an operating head of 15 m and discharge of 0.04 m^3/s. The pump is to be directly connected with a motor operating at 1450 rpm.

Solution

Since the impeller to be designed is the double-suction type, each side of the inlet will handle a discharge of 0.02 m^3/s.

1. *Specific speed* The specific speed is computed from Eq. (10.12).

$$\eta_s = n\sqrt{\frac{Q}{H^{3/4}}}$$

$$= \frac{1450\sqrt{0.04/2}}{15^{3/4}}$$

$$= 26.9$$

2. *Water horse power*

$$\text{WHP} = \frac{QH}{76} = \frac{0.04 \times 1000 \times 15}{76}$$

$$= 7.9 \text{ (say 8.0)}$$

The expected pump efficiency for a specific speed of 26.9 and pump discharge of 40 1/s is 78 per cent (Fig. 10.5).

Thus, the brake horse power, bhp = $\frac{\text{WHP}}{\eta} = \frac{8}{0.78} = 10.26$

3. *Shaft diameter* The shaft diameter is obtained from Eq. (10.14):

$$D_s = \sqrt[3]{\frac{16\,T_s}{\pi\, f_s}}$$

Torque T_s, based on brake horse power, is obtained from Eq. (10.15).

$$T_s = \frac{715\text{ bhp}}{n} = \frac{715 \times 10.26}{1450}$$

$$= 5.06 \text{ kg-m}$$

The shaft is made of mild steel, for which a safe shear stress of 3×10^6 kg/m^2 is assumed.

$\therefore$ The shaft diameter, $D_s = \sqrt[3]{\frac{16 \times 5.06}{\pi \times 3 \times 10^6}}$

$$= 0.020 \text{ m} = 2.0 \text{ cm}$$

The shaft diameter of 2.0 cm satisfies the requirements of torque only. With a view to satisfying the requirements of the bending moment (which cannot be determined at this stage), the shaft diameter is assumed to be 2.5 cm.

4. *Hub diameter* The hub diameter D_H is usually taken one cm more than the diameter of the shaft. Therefore, D_H is assumed to be 3.5 cm.
5. *Impeller inlet dimension and vane angles*
   (a) Diameter of suction flange: The diameter of the suction flange is obtained from Eq. (10.19).

$$D_{su} = \sqrt{\frac{4\,Q}{V_{su} \times \pi}}$$

Assuming the velocity of flow, V_{su} at the suction flange as 3 m/s,

$$D_{su} = \sqrt{\frac{4 \times .04}{\pi \times 3}} = 0.13 \text{ m}$$

$$= 13 \text{ cm}$$

   (b) Diameter of eye of impeller: Using Eq. (10.20), the diameter of the eye of the impeller is

$$D_0 = \sqrt{\frac{4}{\pi} \times \frac{Q'}{2C_0} + D_H^2}$$

Assuming leakage losses as 2%,

$$Q' = 1.02\,Q$$

The velocity at the eye of the impeller is taken slightly more than the velocity of flow at the suction flange. Hence, C_0 is assumed to be 3.20 m/s.

$$D_0 = \sqrt{\frac{4}{\pi} \times \frac{1.02 \times .04}{2 \times 3.20} + \left(\frac{3.5}{100}\right)^2}$$

$$= 0.09 \text{ m} = 9.0 \text{ cm}$$

   (c) Inlet vane edge diameter: The inlet vane edge diameter D_1 is assumed the same as the diameter of the eye of the impeller. Therefore, the value of D_1 adopted is 9.0 cm.

   (d) Passage width of the impeller at inlet: The passage width of the impeller at the inlet is obtained from Eq. (10.21).

$$b_1 = \frac{Q}{\pi\, D_1\, C_{m1} \in_1}$$

The contraction factor $\in_1$ is assumed to be 0.85, The radial inlet velocity C_{m1} is usually adopted slightly higher than the velocity at the eye of the impeller, C_0. Since C_0 is 3.20 m/s, the value of C_{m1} is assumed to be 3.40 m/s.

$$b_1 = \frac{0.04}{2 \times \pi \times 0.09 \times 3.40 \times 0.85}$$

$$= 0.024 \text{ m}$$

$$= 2.4 \text{ cm per side}$$

(e) Inlet vane angle: $\tan \beta_1$ is given by C_{m1}/u_1, where

$$u_1 = \frac{\pi D_1 n}{60} = \frac{\pi \times 0.09 \times 1450}{60}$$

$$= 6.82 \text{ m/s}$$

$$\therefore \qquad \tan \beta_1 = \frac{3.40}{6.82} = 0.50$$

Hence $\beta_1 = 26° 33'$

6. *Outlet vane angle and dimensions*

(a) Outlet diameter of impeller: Using Eq. (10.23), the outlet diameter of the impeller is obtained from the following relationship:

$$D_2 = \frac{84.5 \phi \sqrt{H}}{n}$$

Assuming the value of the head coefficient ϕ to be 1.05 (Sec. 10.1.1),

$$D_2 = \frac{84.5 \times 1.05 \times \sqrt{15}}{1450} = 0.24 \text{ m}$$

$$= 24 \text{ cm}$$

(b) Outlet vane angle: As discussed in See. 10.1.2, the outlet vane angle β_2 is assumed larger than the inlet vane angle, to obtain a smooth and continuous passage of water in the pump casing. Therefore, the value of the vane angle β_2 adopted is 30º (usually the value of β_2 varies from 15º to 40º).

(c) Outlet passage width: The outlet passage width b_2 is obtained from Eq. (10.24).

$$b_2 = \frac{Q'}{C_{m2} \pi D_2 \in_2}$$

The radial velocity C_{m2} is assumed slightly less than the radial velocity at inlet C_{m1}. Since C_{m1} has been assumed to be 3.40 m/s, the value of Cm_2 is assumed to be 3.25 m/s. The contraction factor $\in_2$ (Sec. 10.1.2) is assumed to be 0.925 and the leakage loss 2%. Hence,

$$b_2 = \frac{1.02 \times .04}{3.25 \times 0.24 \times \pi \times 0.925}$$

$$= 0.018 \text{ m} = 1.8 \text{ cm}$$

The dimensions of the pump are compiled as follows:

1. Shaft diameter, D_s	= 2.0 cm
2. Hub diameter, D_H	= 3.5 cm
3. Diameter of suction flange, D_{su}	= 13.0 cm
4. Diameter of eye of impeller, D_0	= 9.0 cm
5. Velocity through the impeller eye, C_0	= 3.20 m/s
6. Inlet vane edge, diameter D_1	= 9.0 cm

7. Radial component of inlet velocity, Cm_1 = 3.40 m/s
8. Inlet vane angle, β_1 = 26° 33′
9. Outlet diameter of impeller, D_2 = 24 cm
10. Outlet vane angle, β_2 = 30°
11. Passage width at inlet, per side, b_1 = 2.4 cm
12. Passage width at outlet, b_2 = 1.8 cm

Example 10.2 Design a closed impeller with one-side suction for a centrifugal pump, for a discharge capacity of 1.5 m^3/min of water, at an operating head of 20 m. The pump is to be directly coupled to an electric motor operating at 1450 rpm.

Solution

1. *Specific speed of the pump*

By Eq. (10.12), the specific speed

$$\eta_s = \frac{n\sqrt{Q}}{H^{3/4}}$$

In the present case,

$$n = 1450 \text{ rpm}$$

$$H = 20 \text{ m}$$

$$Q = 1.5 \text{ m}^3/\text{min} = 0.025 \text{ m}^3/\text{s}$$

$$\eta_s = \frac{1450\sqrt{0.025}}{20^{3/4}} = 24.2$$

2. *Water horse power*

$$\text{whp} = \frac{QH}{76} = \frac{0.025 \times 1000 \times 20}{76}$$

$$= 6.67$$

The expected efficiency for a pump specific speed of 24.2 and pump discharge of 25 1/s is 72 per cent (Fig. 10.5).

Thus, the brake horse power, $\text{bhp} = \frac{\text{whp}}{\eta} = \frac{6.67}{0.72} = 9.26$

3. *Shaft diameter*

The shaft diameter is obtained from Eq. (10.14).

$$D_s = \sqrt[3]{\frac{16\,T_s}{\pi\, f_s}}$$

Torque T_s, based on brake horse power, is obtained from Eq. (10.15),

$$T_s = \frac{715 \times \text{bhp}}{n} = \frac{715 \times 9.26}{1450} = 4.56 \text{ kg-m}$$

The shaft will be made of mild steel, for which a safe shear stress may be assumed to be 3×10^6 kg/m^2.

Hence, the shaft diameter, D_s

$$= \sqrt[3]{\frac{16 \times 4.56}{\pi \times 3 \times 10^6}}$$

$$= 0.020 \text{ m} = 2.0 \text{ cm}$$

The shaft diameter of 2.0 cm satisfies the requirements of torque only. Even though it is not possible to determine the bending moment at this stage, yet, to take care of it, the shaft diameter is assumed to be 2.5 cm.

4. *Hub diameter*

   As discussed in See. 10.1.2, the hub diameter is assumed 1 cm more than the diameter of the shaft. Thus, the diameter of the shaft is assumed to be 3.5 cm.

5. *Impeller inlet dimensions and vane angles*

   (a) Diameter of suction flange: The diameter of the suction flange is obtained from Eq. (10.19),

   $$D_{su} = \sqrt{\frac{4\,Q}{\pi\, V_{su}}}$$

   Assuming the velocity of flow V_{su} at the suction flange to be 3 m/s,

   $$D_{su} = \sqrt{\frac{4 \times 0.025}{\pi \times 3}} = 0.10 \text{ m}$$

   The diameter of the suction flange = 10 cm

   (b) Diameter of the eye of the impeller: Using Eq. (10.20), the diameter of the eye of the impeller is

   $$D_0 = \sqrt{\frac{4}{\pi}\frac{Q'}{C_0} + D_H^2}$$

   Considering the leakage losses as 2%, Q' is 0.0255 m^3/s. The velocity of water at the eye of the impeller is assumed slightly more than the velocity at the suction flange. Hence, C_0 is assumed to be 3.25 m/s.

   $$\therefore \qquad D_0 = \sqrt{\frac{4}{\pi \times 3.25} \times 0.0255 + \left(\frac{3.5}{100}\right)^2}$$

   $$= 0.106 \text{ m}$$

   $$= 10.6 \text{ cm} \quad \text{say } 11.0 \text{ cm}$$

   (c) Inlet vane edge diameter: The inlet vane edge diameter is assumed the same as the diameter of the eye of the impeller. Therefore, D_1 is equal to D_0 = 11.00 cm.

   (d) Passage width at inlet: The width of the impeller at the inlet is obtained from Eq. (10.21),

$$b_1 = \frac{Q}{\pi\, D_1\, C_{m1} \in_1}$$

The contraction factor $\in_1'$ may be assumed to be 0.85. The radial inlet velocity C_{m1} is usually adopted slightly higher than the velocity at the eye of the impeller, C_0. Since C_0 is 3.25 m/s, C_{m1} may be assumed to be 3.50 m/s.

$$\therefore \qquad b_1 = \frac{0.025}{\pi \times 0.11 \times 3.50 \times 0.85}$$

$$= 0.024 \text{ m}$$

$$= 2.4 \text{ cm}$$

(e) Inlet vane angle: As discussed in Sec. 10.1.1, α_1 = 90° tan β_1 is given by C_{m1}/u_1. The tangential inlet velocity is obtained from the following relationship:

$$u_1 = \frac{\pi\, D_1\, n}{60} = \frac{\pi \times 0.11 \times 1450}{60}$$

$$= 8.3 \text{ m/s}$$

$$\therefore \qquad \tan \beta_1 = \frac{3.5}{8.3} = 0.42$$

Hence $\qquad \beta_1 = 22° \, 46' 57''$

6. *Outlet Vane Angle and Dimensions*

(a) Outlet diameter of impeller: Using Eq. (10.23), the outlet diameter of the impeller is

$$D_2 = \frac{84.5\, \phi \sqrt{H}}{n}$$

Assuming the value of the head coefficient ϕ to be 1.05 (Sec. 10.1.1),

$$D_2 = \frac{84.5 \times 1.05 \times \sqrt{20}}{1450} = 0.274 \text{ m}$$

$$= 27.4 \text{ cm}$$

(b) Outlet vane angle: As discussed in Sec. 10.1.2, 30° the outlet vane angle β_2 is assumed larger than the inlet vane angle, to obtain a smooth and continuous passage. The vane angle β_1 = 22° 46′ 57″. Therefore, the value of β_2 adopted is 30 (The values of β_2 vary usually from 15° to 40°).

(c) Outlet passage width: The outlet passage width b_2 is given by Eq. (10.24),

$$b_2 = \frac{Q}{C_{m_2}\, D_2\, \pi \in_2}$$

The radial velocity at the outlet, C_{m2}, is assumed slightly less than the radial velocity at the inlet, C_{m1}. Since C_{m1} has been assumed to be 3.50 m/s, the value of C_{m2} adopted is 3.25 m/s. The value of the contraction factor at the outlet $\in_2$, as discussed in Sec. 10.1.2, is assumed to be 0.925. Since the outlet area is based on the total flow, i.e. design discharge plus leakage, Q' is assumed to be 0.0255 m^3/s, allowing a leakage loss of 2 per cent.

$$b_2 = \frac{0.0255}{3.25 \times 0.274 \times \pi \times 0.925}$$
$$= 0.01 \text{ m}$$

(d) Outlet velocity diagram: The peripheral velocity u_2 of the impeller is estimated from the relationship expressed in Eq. 10.25.

$$u_2 = \frac{\pi D_2 n}{60} = \frac{\pi \times 0.274 \times 1450}{60}$$
$$= 20.79 \text{ m/s}$$

The virtual tangential component, Cu_2 of the absolute outlet velocity C_2 is obtained from Eq. (10.26)

$$Cu_2 = u_2 - \frac{C_{m2}}{\tan \beta_2}$$
$$= 20.79 - \frac{3.25}{\tan 30^\circ} = 20.79 - \frac{3.25}{0.577}$$
$$= 15.16 \text{ m/s}$$

Assuming the value of $\eta_\infty = 0.7$, (refer section 10.1.1), the actual tangential component of absolute outlet velocity

$$Cu'_2 = Cu \times \eta_\infty = 15.16 \times 0.7$$
$$= 10.6 \text{ m/s}$$

The tangent of the actual angle α'_2 is obtained from Eq. (10.27)

$$\tan \alpha'_2 = C_{m2}/Cu'_2 = \frac{3.25}{10.6} = 0.307$$

$\therefore$ $\alpha'_2 = 17^\circ$

The actual absolute outlet velocity (Eq. 10.28)

$$C'_2 = \sqrt{C_{m2}^2 + Cu_2'^2}$$
$$= \sqrt{(3.25)^2 + (10.6)^2}$$
$$= 11.08 \text{ m/s}$$

The outlet velocity diagram is shown in Fig 10.8.

Design of Vanes

The radial components of absolute velocity at the inlet and outlet ends, C_{m1} and C_{m2} are 3.5 m/s and 3.25 m/s, respectively. The relative velocities w_1 and w_2 are calculated from the relationship sin $\beta = C_m/w$. The relative velocities w_1 and w_2, corresponding to vane angles β_1 (22° 46′ 57″) and β_2 (30°)

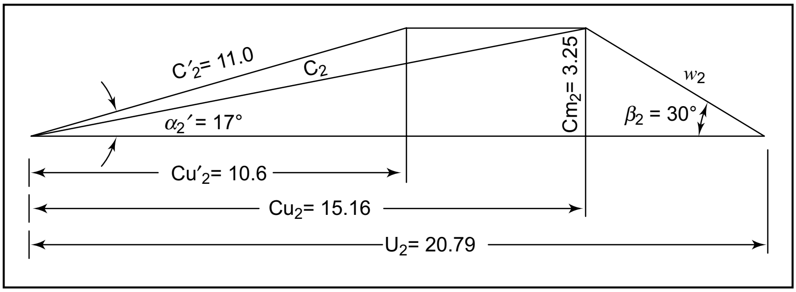

Fig. 10.8 Outlet velocity diagram of Example 10.2

and C_{m1} and C_{m2} are 8.8 and 7.0 m/s at the inlet and outlet ends, respectively. For the known values of the radial component of absolute velocities, relative velocities, and corresponding radii (5.5 cm and 13.7 cm at the inlet and outlet, as D_1 = 11 cm and D_2 = 27.4 cm), the intermediate values of radial components of absolute velocities, and relative velocities, corresponding to various radii, are calculated proportionately. The values of β corresponding to the established intermediate values of C_m and w are calculated.

(i) Tangent Arcs

The impeller is arbitrarily divided into a number of concentric rings between radii r_1 and r_2 (5.5 cm, 7.5 cm, 9.5 cm, 11.5 cm and 13.7 cm). The radius of arc ρ, defining the shape between any two rings r_b, and r_a, is obtained from the relationship,

$$\rho = \frac{r_b^2 - r_a^2}{2(r_b \cos\beta_b - r_a \cos\beta_a)}$$

The computations of the values of ρ for various ring sizes are shown in Table 10.1. The layout of the vane for the calculated radii of arcs is shown in Fig. 10.9. The procedure in developing the tangent arcs is as follows:

TABLE 10.1 Computed Data for Determination of Radius of Arc in Example 10.2

Ring	r cm	r^2 cm^2	β	$\cos\beta$	$r\cos\beta$	$r_b\cos\beta_b - r_a\cos\beta_a$	$r_b^2 - r_a^2$	ρ cm
1	5.5	30	22° 46′	0.93	5.12			
						1.78	26	7.30
X	7.5	56	23° 50′	0.92	6.90			
						1.75	34	9.71
Y	9.5	90	25° 06′	0.91	8.65			
						1.47	42	14.29
Z	11.5	132	28° 24′	0.88	10.12			
						1.80	56	18.33
2	13.7	188	30° 0°′	0.87	11.92			

Source: The subscripts *a* and *b* indicate concentric rings starting from the first ring to the last ring.

Since the arcs are tangent to each other, the centres of adjacent arcs lie on a line with their point of tangency. A radial line *OJ* (Fig. 10.9) is drawn from the centre of rotation 0 to the radius r_1. With *J* as apex, an angle *OJK* of 22º 46′ (β_1) is drawn. The centre *K* for the first arc must lie on this line, at a distance of 7.3 cm (ρ_1) from *J*. A line drawn through the point of intersection of this arc with the ring *x* of radius 7.5 cm (point *L*) and (*K*) must have the centre for the second arc *M*. The procedure is repeated until the outside ring at radius r_2 is reached. The accuracy of the plot is checked by measuring angle *OSR* where *R* is the centre of the last arc. In Fig. 10.9, angle *OSR* is 30º. Since it is equal to β_2, the accuracy of plotting is confirmed.

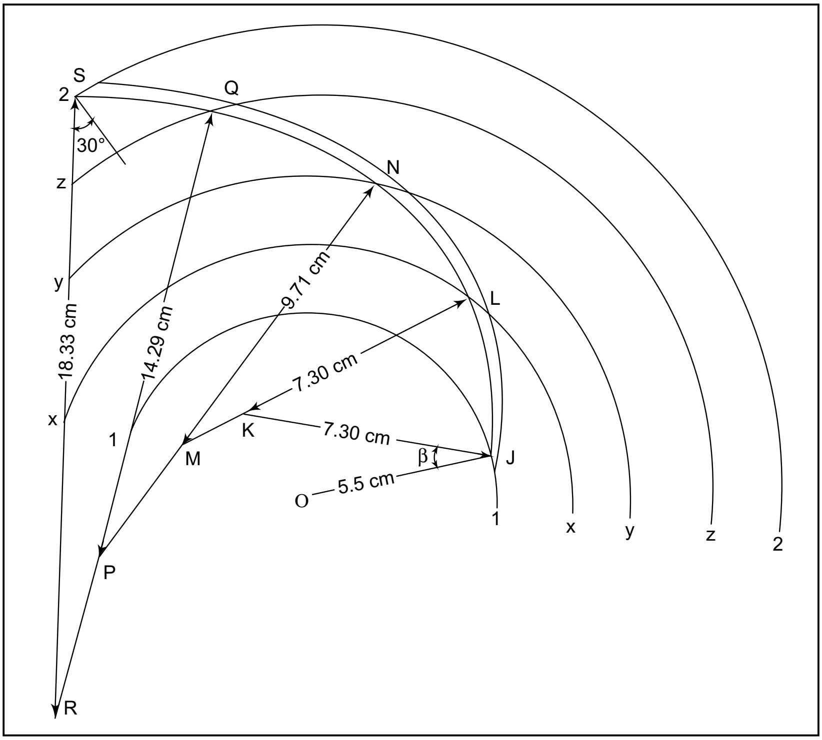

Fig. 10.9 Design of vanes using the method of tangent arcs in Example 10.2

(*i*). *Vane Thickness*

A uniform thickness of 3 mm is adopted for the vane, as per Sec. 10.1.2

(*ii*). *Number of Vanes*

The number of vanes is determined using Eq. (10.30),

$$Z = 6.5\ \frac{D_2 + D_1}{D_2 - D_1} \times \sin\frac{(\beta_1 + \beta_2)}{2}$$

$$\frac{\beta_1 + \beta_2}{2} = \frac{22^\circ\ 46' + 30^\circ}{2} = 26^\circ\ 23'28''$$

The number of vanes

$$Z = 6.5\left(\frac{27.4+11.0}{27.4-11.0}\right)\sin\ 26^\circ\,23'28''$$

$$= 6.5 \times \left(\frac{27.4+11.0}{27.4-11.0}\right) \times 0.444$$

$$= 6.8, \quad \text{say } 7$$

(iv). Passage Width

The passage width is obtained from Eq. (10.33),

$$b = \frac{Q}{\pi\, D \in C_m}$$

where $\in$ = contraction factor

$$= \frac{\pi\, D - \dfrac{Zt}{\sin\beta}}{\pi\, D}$$

The calculations for the passage width are shown in Table 10.2.

TABLE 10.2 Computed Data for Determining the Passage Width for Impeller in Example 10.2

r cm	D cm	πD cm	t cm	$\sin\beta$	$\frac{Zt}{\sin\beta}$	$\pi D - \frac{Zt}{\sin\beta}$	$\in$	C_m m/s	b cm
5.5	11	34.54	0.30	0.367	5.7	28.84	0.81	3.50	2.55
7.5	15	47.10	0.30	0.405	5.2	41.90	0.89	3.43	1.73
9.5	19	59.66	0.30	0.424	5.0	54.66	0.91	3.37	1.44
11.5	23	72.22	0.30	0.476	4.4	67.82	0.94	3.31	1.20
13.7	27.4	86.04	0.30	0.50	4.2	81.84	0.95	3.25	1.09

The dimensions of the designed impeller are as follows:

1. Shaft diameter, D_s = 2.5 cm
2. Hub diameter, D_H = 3.5 cm
3. Diameter of suction flange, D_{su} = 10 cm
4. Velocity through the suction flange, V_{su} = 3.0 m/s
5. Diameter of eye of impeller, D_0 = 11 cm
6. Velocity through the impeller eye, C_0 = 3.25 m/s
7. Inlet vane-edge diameter, D_1 = 11 cm/s
8. Radial component of inlet velocity, C_{m1} = 3.50 m/s
9. Inlet vane angle, β_1 = $22^\circ\,46'57''$
10. Outside diameter of impeller, D_2 = 27.4 cm
11. Outlet vane angle, β_2 = 30°

12. Peripheral velocity at outlet, u_2	= 20.79 m/s
13. Virtual tangential component of absolute velocity at outlet, Cu_2	= 15.16 m/s
14. Actual tangential component of absolute velocity at outlet, Cu_2'	= 10.6 m/s
15. Actual outlet angle, i.e. angle of water leaving impeller, α_2'	= 17º
16. Actual absolute velocity at outlet, C_2'	= 11.08 m/s
17. Relative velocity at the inlet, w_1	= 8.8 m/s
18. Relative velocity at outlet, w_2	= 7.0 m/s
19. Number of vanes, Z	= 7
20. Passage width at inlet, b_1	= 2.55 cm
21. Passage width at outlet, b_2	= 1.09 cm

EXAMPLE 10.3 Design a volute to fit the impeller designed in Example 10.2.

Solution

The cross-section of the volute is assumed to be trapezoidal, with the apex angle of 60º, which provides the side slope to be used. The width at the outlet, b_2 = 1.09 cm.

The base width of the volute for a low specific speed (Sec. 10.1.2) is assumed to be twice the width at the impeller outlet, i.e. $b_3 = 2 \times 1.09 = 2.18$ cm

Angle θ°, measured from an assumed radial line, is determined by Eq. (10.34),

$$\theta° = \frac{360\, r_2\, Cu_2'}{Q} \int_{r_2}^{r_\theta} b \frac{dr}{r}$$

When r and b are expressed in cm, Eq. (10.34) becomes

$$\theta° = 360° \times \frac{13.7}{100} \times \frac{10.6}{.025} \times \frac{1}{100} \int_{r_2}^{r_\theta} b \frac{dr}{r}$$

$$= 209 \int_{r_2}^{r_\theta} b \frac{\Delta r}{r}$$

The solution of the above equation is presented in Table 10.3. In Table 10.3, Column 1 indicates radii equal to the outside radius of the impeller and greater, forming rings having areas $b_{ave} \times (\Delta r)$. The average width of each ring,

$$b = b_3 + 2x \tan \theta/2$$
$$= 2.18 + 2\,(R_{ave} - 13.7) \tan 60°/2$$

TABLE 10.3 Solution of Eq. (10.34) in Example 10.3

r cm	Δr cm	r_{av} cm	b_{av} cm	$\frac{b\,\Delta r}{r_{av}}$	$\Delta\theta$°	θ°	ΔA cm^2	A_θ cm^2	$Q\theta$ m^3/s	V_{av} m/s
13.7						0		0	0	
	0.8	14.10	2.64	0.15	31.35		2.11			
14.5						31.35		2.11	.0022	10.42
	0.5	14.75	3.34	0.12	25.05		1.67			
15						56.40		3.78	.0039	10.30
	2.0	16.0	4.80	0.60	125.4		9.60			

(*Contd.*)

TABLE 10.3 (*Contd.*)

r cm	Δr cm	rav cm	b_{av} cm	$\frac{b\,\Delta r}{r_{av}}$	$\Delta\,\theta^{o}$	θ^{o}	ΔA cm^2	A_θ cm^2	$Q\theta$ m^3/s	V_{av} m/s
17						181.80		13.38	.0126	9.41
	1.0	17.5	5.69	0.32	66.88		5.69			
18						248.68		19.07	.0173	9.07
	1.0	18.5	7.40	0.40	83.6		7.40			
19						332.28		26.47	.0230	8.68
	1.0	19.5	8.30	0.42	87.78		8.30			
20						420.06		34.77	.029	8.34

Column 5 indicates the value of $\frac{b \times \Delta r}{r_{ave}}$, which is multiplied by 209 to obtain the angle increments to $\Delta\theta^{\circ}$ in Col. 6. The above values are integrated by successive additions in Col. 7. The incremental areas ΔA (incremental radius x average width) are given in Col. 8, which are integrated by successive additions in Col. 9.

The flow past the section $\frac{Q_\theta}{360}$ is presented in Col. 10. The average velocity at these sections is obtained by dividing the values of the discharge by the corresponding area of flow (Col. 11). The velocities obtained above are reduced by about 10 per cent to allow for friction loss in the volute. The velocities near the tongue are further decreased by increasing the area, to avoid excessive losses due to the improper angle, at capacities other than the design discharge.

Tongue Radius

The volute starts at the tongue with a radius r_t, which is 5 to 10 per cent greater than the impeller radius r_2 (Fig. 10.10). Therefore, tongue radius = 1.05 r_2 to 1.10 r_2, r_2 = 13.7 cm

Hence, a value of 14.5 cm may be used.

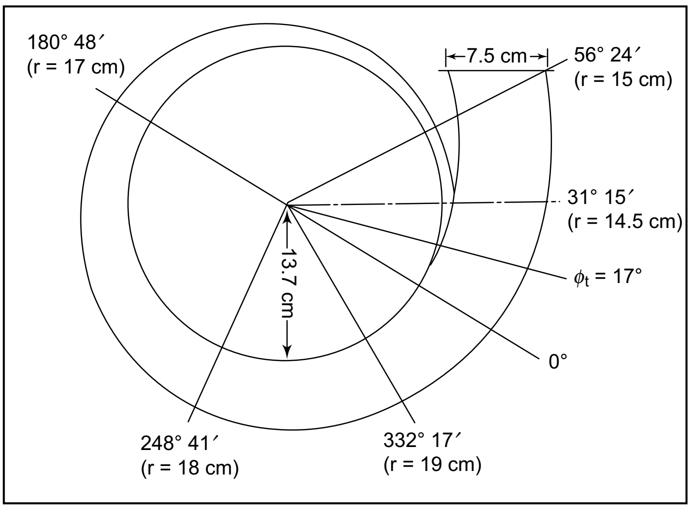

Fig. 10.10 Design dimensions of volute in Example 10.3

Tongue Angle

The tongue angle is obtained from Eq. (10.36),

$$\theta_t = \frac{132 \log_{10} \dfrac{r_t}{r_2}}{\tan \alpha_2'}$$

$$= \frac{132 \log_{10} \dfrac{14.5}{13.7}}{\tan 17^\circ}$$

$$= \frac{132 \times 0.025}{0.3057} = 10^\circ\, 47'$$

Discharge Flange

The desirable velocity at which the water leaves the pump is between 5.5 to 7.5 m/s (Sec. 10.1.2). Assuming a velocity of 6 m/s, the required area of the flange is 0.025/6 = 0.00417 m^2 = 41.7 cm^2. If d is the diameter of the flange,

$$\frac{\pi d^2}{4} = 41.7$$

or $$d = \sqrt{\frac{41.7 \times 4}{\pi}} = 7.29 \text{ cm}$$

Hence, a flange of diameter 7.5 cm is adopted.

The section of the volute passage at the calculated point is shown in Fig. 10.10. A view of the front elevation of the volute is shown in Fig. 10.11.

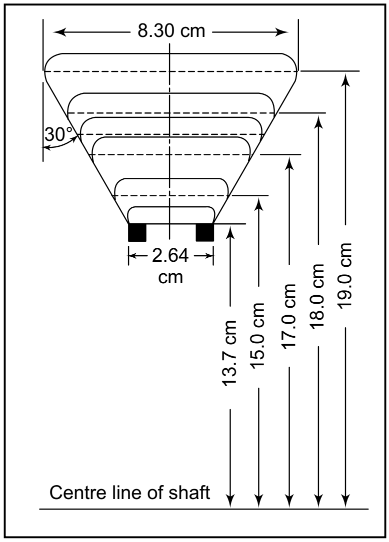

Fig. 10.11 Design sketch of volute in Example 10.3

10.2 CENTRIFUGAL PUMP INSTALLATION

Efficient operation of a centrifugal pump depends on its proper installation, operation and maintenance. Since the overwhelming majority of irrigation pumps are of the centrifugal type, details pertaining to their installation under widely varying site conditions require careful attention. The type of installation depends on the nature of the water source (surface water bodies/ground water), type of well (open well/tube well), extent of lining in case of open wells, seasonal variations in static water level, and the kind of prime mover used in operating the pump (electric motor/diesel engine). Bureau of Indian Standards has presented specific requirements for various components of the pumping system (IS: 10804–1994).

Proper installation of a centrifugal pump ensures its efficient service. Many of the operating difficulties related to the pumps occur due to faulty installation. The various steps involved in the installation of a horizontal centrifugal pump include its location, foundation, alignment and piping under different site conditions.

10.2.1 Location

The correct location of a horizontal centrifugal pump with respect to the water level is important. The pump should be installed as close as possible to the water level, but without submerging it. This will result in minimizing the suction lift and permit the use of a short and direct suction line. As per Bureau of Indian Standards (IS 9694: Part 1-1987), the pump should be installed in such a way as to limit the total suction lift, including drawdown and friction losses to 4.5 m. An increase in suction lift will reduce the pump capacity and lower its efficiency. The maximum practical limit of suction is about 6.5 m. It is important that the pumps is so located that it is accessible to inspection and maintenance. It should be located in a dry and ventilated place.

Effect of Suction Lift on Discharge and Efficiency

The effect of increase in suction lift on the discharge of horizontal centrifugal pumps is shown in Fig. 10.12. It is evident from Fig. 10.12 that the discharge decreases with increase in suction lift. Initially, the rate of decrease is low, but beyond a suction lift of 4.5 m, it increases rapidly. This decrease in discharge is because of a decrease in the available net positive suction head (NPSH), which is a function of the static suction lift. The excess of available NPSH over the required NPSH reduces, which is the only source of energy for water to move up in the suction pipe. This difference is minimised at a higher suction lift and causes a drastic reduction in discharge.

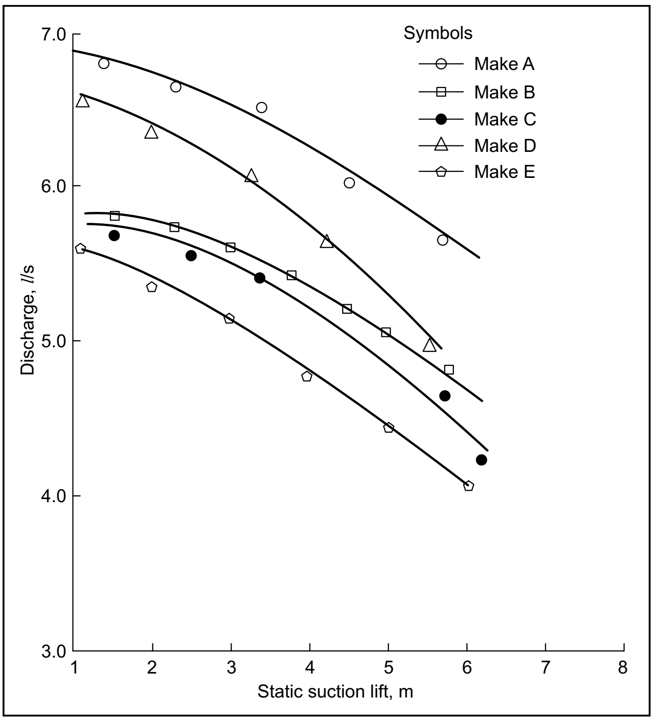

Fig. 10.12 Relationship between static suction lift and discharge in different makes of horizontal centrifugal pumps

Beyond a particular limit of suction lift, the pump may not operate at all. This critical limit may occur when the difference between the available and required NPSH becomes equal to or less than zero.

10.2.2 Pump Foundation

The centrifugal pump is to be installed on a foundation rigid enough to support the load of the unit and prevent any twisting or misalignment, as well as absorb all vibrations. A reinforced cement concrete or reinforced brick cement masonry base of adequate dimensions is usually used as foundation for the pump and prime mover. Sometimes, however, steel girders or wooden beams are used as foundations for pumps.

Design Considerations

The following are the basic points to be considered while designing the foundation of a horizontal centrifugal pump:

1. The pump foundation should be kept independent of the foundation of the pump house.
2. The entire weight of the pumping set should be accommodated on the same foundation to avoid distortion of the machine shaft due to differential settlement.
3. The dimensions of the pump foundation is so fixed that the resultant force due to the weight of the pumping set and that of the foundation pass through the centre of gravity of the base contact area.
4. The weight of the foundation and the contact area should satisfy the vibration requirements. As a thumb rule, the weight of the foundation should be at least 2.5 times the weight of the pumping set.
5. The maximum intensity of loading must be less than the allowable bearing pressure that the soil will safely carry without the risk of shear failure, irrespective of any foundation settlement that may result. The safe bearing capacity of various soils is given in Table 10.4.
6. The surface area of the foundation should be sufficient to leave adequate space around the pump set, in order to allow grouting of foundation bolts.
7. The depth of foundation may vary from 50 to 75 cm. However, the weight of the foundation should satisfy the criteria of 2.5 times the weight of the pump set.
8. The minimum reinforcement for foundation should be 50 kg/m^3 of concrete/brickwork.
9. The minimum diameter of the steel bars should be 12 mm. The spacing between the bars should not be more than 200 mm.
10. The diameter of the foundation bolts for the installation of a horizontal centrifugal pump varies from 12 to 20 mm, with a prime mover rating of 1.5 to 11 kW, respectively. The length of the bolts vary from 15 to 45 cm.
11. Usually, cement concrete 1 : 2 : 4 is used for foundation. However, for small-size pump sets, brick cement masonry with 1 : 4 cement mortar may be used.

Design Procedure

The following is the step-by-step procedure in the design of pump foundations:

1. Determine the type of soil on which the foundation is to be constructed.
2. Determine the safe bearing capacity of the soil (Table 10.4).

TABLE 10.4 Safe Bearing Capacity of Soils*

Serial no.	Type of rock/soils	Safe bearing capacity kg/cm^2
1.	*Rocks*	
(i)	Hard rocks without lamination and defects (e.g. granite, trap and diorite)	3.3
(ii)	Laminated rocks (e.g. sandstone and limestone in good condition)	16.5
(iii)	Residual deposits of shattered and broken bed rock and hard-shale	9.0
(iv)	Soft rock	4.5
2.	*Non-cohesive soils*	
(v)	Gravel and sand, compact and offering high resistance to penetration when excavated by tools	4.5
(vi)	Compact and dry coarse sand	4.5
(vii)	Medium sand, compact and dry	2.5
(viii)	Fine sand and silt	1.5
(ix)	Loose gravel or sand-gravel mixture, loose, coarse-to-medium sand, dry	2.5
(x)	Loose and dry fine sand	1.0
3.	*Cohesive soils*	
(xi)	Soft shale, hard or stiff clay in deep bed, dry	4.5
(xii)	Medium clay, readily indented with a thumb nail	2.5
(xiii)	Moist clay and sandy clay mixture which can be indented with strong thumb pressure	1.5
(xiv)	Soft clay	1.0
(xv)	Very soft clay which can be easily penetrated with thumb	0.5

Source: In case of expansive clays, peat and earth fills, the bearing capacity varies greatly and should be determined after *in situ* test
* Based on Bureau of Indian Standards (IS 1904:1986)

3. Determine the design load which includes the following:
   (a) Dead mass of the foundation (The foundation size may be assumed to calculate the dead mass).
   (b) Total mass of pump multiplied by 3 (to take care of the dynamic forces).
4. Divide the design load by the safe bearing capacity of the soil, to determine the required base area of the foundation.

5. Determine the functional requirement of the pump, as per item (6), under design considerations.
6. The base area of the foundation selected will be either of the areas determined to satisfy the design or functional requirement, whichever is more.
7. The depth of foundation under normal conditions may be taken to be 60 cm.
8. The actual load of the designed foundation is again calculated. The load per unit area must be less than the safe bearing capacity of the soil, otherwise the design calculations are revised with new assumptions of the foundation size.
9. The inside diameter of the pipe sleeves for embedding the anchor bolts may be approximately two and a half times the diameter of the anchor bolt.

Example 10.4 Design the foundation of a horizontal centrifugal pump coupled with an electric motor of 5 kW capacity. The base plate is of 50 cm × 75 cm. The soil is fine sand, loose and dry. The weight of the pump set is 500 kg.

Solution

1. *Foundation size*. Assuming the foundation size to be 90 cm × 65 cm × 60 cm, the dead mass of the foundation is:

$$= \frac{90 \times 65 \times 60}{100 \times 100 \times 100} \times 2500 \quad \text{(assuming the weight of cement concrete to be } 2500 \text{ kg/ m}^3\text{)}$$

$$= 877.5 \text{ kg}$$

$\therefore$ Design load = 500 × 3 + 877.5 = 2377.5 kg

Safe bearing capacity of soil = 1 kg/cm^2 (Table 10.4)

Design area of foundation = 2500/1 = 2500 cm^2

Size of the base plate = 75 cm × 50 cm

Assuming that a 7.5 cm wide space is provided all round the base plate, the functional requirement of the area = 90 × 65 = 5850 cm^2.

Since the functional area required is more than the area needed from the design point of view, the size of the foundation may be taken to be 90 cm × 65 cm. The depth of the foundation may be taken to be 60 cm. The foundation may be laid on a compacted bed of brick or stone ballast.

Actual design load

$$= 500 \times 3 + \frac{90 \times 65 \times 60}{100 \times 100 \times 100} \times 2500 = 2377.5 \text{ kg}$$

or $$\frac{2377.5}{5850} \text{ kg/cm}^2 = 0.41 \text{ kg/cm}^2$$

Since the actual load (kg/cm^2) is much less than the safe bearing capacity of the soil, the design is safe.

2. *Reinforcement*. Steel bars of 15 mm diameter may be provided at a spacing of 200 mm.
3. *Anchor bolt*. Anchor bolts of 15 mm diameter may be provided in pipe sleeves of 40 mm inside diameter. The design details are given in Fig. 10.13.

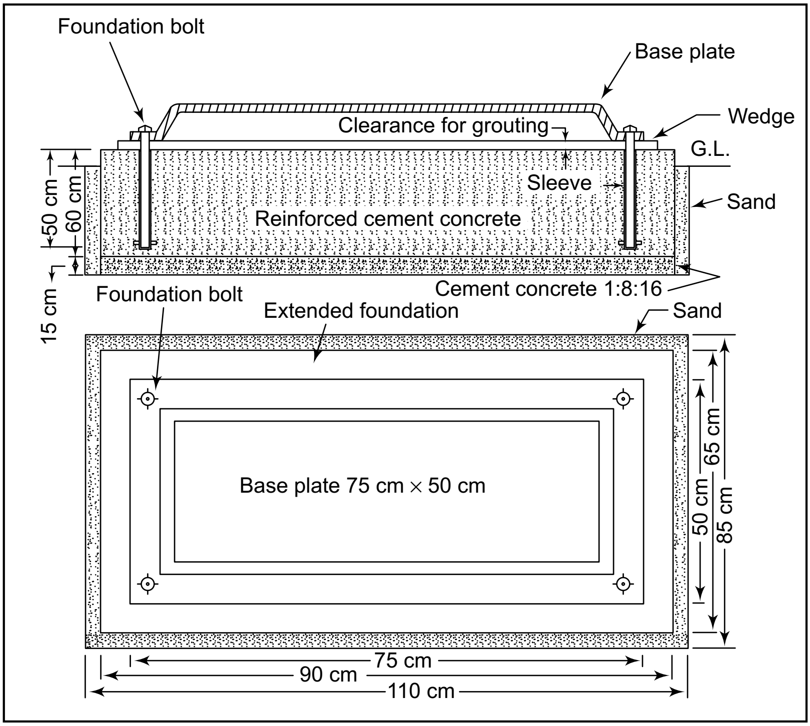

Fig. 10.13 Detail of the foundation for the installation of an engine/motor operated centrifugal pump (Example 10.4).

Construction Procedure

The cement concrete used for the foundation usually has a mix ratio of 1: 2: 4. Continuous concreting is done for the entire block, leaving provision for pipe sleeves and groutings. The reinforcement is protected by a cement concrete cover of about 50 mm thickness. The requirements of building materials, such as cement, sand, gravel or crushed stone and brick-bats, are determined for the design section of the foundation (Table 10.5). The building material may be stored at the site before constructing the foundation. The foundation is excavated as per the design requirements. The base of the foundation is well compacted before laying the brick-bats. The reinforcement as well as the cement concrete of proper mix are prepared. Pipe sleeves with anchor bolts are fixed in position before laying the concrete. Usually, a wooden template (Fig. 10.14) is used for hanging foundation bolts while pouring concrete for the foundation of the pumping set. The reinforcement and concreting are done as per the design specifications. Large washers placed on the bolts hold them from slipping through the pipe sleeves (Fig. 10.13). The top of the foundation should be roughened, cleaned and dampened before setting the pump set in position. The pump set is placed on the wedges inserted in between the top of the foundation and the bottom of the base plate.

TABLE 10.5 Requirements of Cement, Sand, Coarse Aggregate and Bricks for Foundation Work

Description	Quantities			
	Cement bags	Sand m^3	Coarse aggregate m^3	Bricks no.
One cubic metre cement concrete				
1. $1 : 1\frac{1}{2} : 3$	8.25	0.43	0.85	–
2. 1 : 2 : 4	6.50	0.45	0.90	–
3. 1 : 3 : 6	4.50	0.47	0.94	–
4. 1 : 4 : 8	3.50	0.48	0.96	–
5. 1 : 5 : 10	2.80	0.49	0.98	–
6. 1 : 6 : 12	2.35	0.495	0.99	–
7. 1 : 8 : 16	1.80	0.50	1.00	–
One cubic metre brick cement mortar masonry				
1. 1 : 2	3.45	0.24	–	480
2. 1 : 3	2.40	0.25	–	480
3. 1 : 4	1.75	0.25	–	480
4. 1 : 5	1.45	0.25	–	480
5. 1 : 6	1.20	0.25	–	480
6. 1 : 7	1.00	0.25	–	480
One square metre cement plaster, 12.5 mm thick				
1. 1 : 2	0.20	0.014	–	–
2. 1 : 3	0.16	0.016	–	–
3. 1 : 4	0.12	0.016	–	–
4. 1 : 5	0.094	0.016	–	–
5. 1 : 6	0.078	0.016	–	–

By adjusting the wedges, the unit is brought to an approximately level position. When this is done, the base plate of the pump is kept 2 to 2.5 cm above the unfinished foundation. Suction and delivery pipe connections are then lightly tightened. After satisfactory leveling, the foundation bolts are tightened, initially by hand.

The space between the base plate and the foundation surface is thoroughly grouted with cement mortar. The grout is composed of one part of cement and two parts of building sand, with sufficient water to flow freely under the base. Grouting helps primarily in preventing lateral movement of the pump base and, secondly, increases its mass, thus reducing vibrations. It also fills irregularities in the foundation.

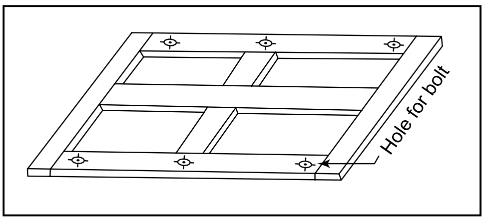

Fig. 10.14 Wooden template for hanging foundation bolts while pouring concrete for foundation of a pumping set

A frame-work is built around the base of the pump set to ensure full grouting. The grout is poured through a hole made on the top of base plate, until the entire space between the foundation and the base plate is filled properly. The grout should be puddled continuously while it is being poured, to expel air and completely fill the space under the base plate to the level of the hole provided at the top of the base plate. The exposed surface of the grout should be covered with wet burlap to avoid cracking due to rapid drying. When the grout is sufficiently set (usually it takes about 48 hours), the frame-work is removed and the finishing of exposed surfaces of the foundation and grout is carried out. The foundation bolts are finally tightened after about 72 hours or more. Care is taken not to tighten the bolts too much or unevenly, as this will tend to distort the base plate and throw the pump out of alignment, causing the bearing to run hot and produce excessive wear.

10.2.3 Alignment

The alignment of the shaft is one of the important considerations in the installation of the pump set. Though the pump and the prime mover combination is usually aligned at the factory premises, there is a possibility of the base plate getting sprung up during transportation, or getting distorted by the unequal tightening of the foundation bolts. Therefore, alignment must be checked before putting the pump set into operation.

Sometimes, there is a belief among users that the flexible coupling takes care of misalignment. It is to be understood that the flexible coupling does not compensate for misalignment. It is used for connecting the shaft of the pump and the prime mover and for transmission of power to the pump. The coupling compensates for temperature changes and permits end movement of shafts without interference with each other.

Misalignment between the pump shaft and drive shaft may be of the following two types (Fig. 10.15):

1. Angular misalignment – shafts with axes concentric but not parallel.
2. Parallel misalignment– shafts with axes parallel but not concentric.

The flexible coupling are mounted on the pump shaft and prime-mover shaft in such a way that the faces of the couplings are parallel to each other and spaced so that the coupling/shaft end cannot strike each other.

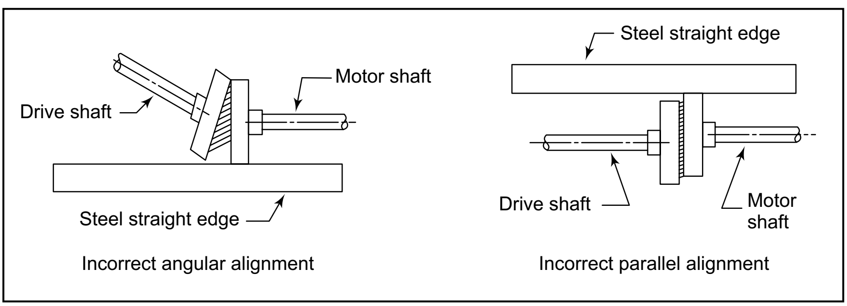

Fig. 10.15 Checking the alignment of the shaft of the prime mover with the pump shaft

Check for Angular Alignment

The angular alignment of pump couplings is checked by inserting a tapet gauge or feeler gauge at four points between the coupling halves, at approximately 90º intervals, around the coupling (Fig. 10.15).

The distances between the faces at the four points are compared. The pump set will be in angular alignment when the measurements show that the coupling faces are the same distance apart at all the four points.

Check for Parallel Alignment

Parallel alignment can be checked by placing a straight edge across both the coupling rims, at the top, bottom and both sides (Fig. 10.15). The pump set will be in parallel alignment when the straight edge rests evenly on the coupling rim at all positions.

Belt Driven Pumps

On belt driven units, the pump and driver shafts must be parallel, except when a quarter-twist belt drive is used. The pulleys also must be properly aligned. The pulleys on both the pump and the driver should be mounted as close to the bearing housing as possible, to minimize overhang and allow sufficient clearance for the end play of the shafts. On flat belt and V-belt drives, the tight side of the belt should be at the bottom. A vertical drive is avoided on flat-belt drives. An angle of 45° or less between the line of shaft centres and the horizontal is desirable. Normally, the belt speed should not exceed about 1500 metres per minute. The ratio of the diameter of the pulleys should not exceed 5:1. The belt tension is adjusted just enough to prevent slippage. Excessive tension overloads the bearings.

10.2.4 Installation in Open Wells

The procedure for installation of centrifugal pumps in open wells depends on the prime mover used, the depth of the pumping water level below the ground level and the condition of well lining.

Installation of Centrifugal Pumps in Shallow Open Wells

Generally, in the case of shallow open wells, the total suction lift is limited to 6.5 m. Therefore, horizontal centrifugal pumps directly coupled to electric motors or diesel engines and mounted on base plates can be installed at the ground surface (Fig. 10.16).

If the speed of the prime mover does not match the required pump speed for direct coupling, a pump set with belt drive is adopted. While pumping from an open well with a diesel engine, if the total suction lift exceeds, say, 6 m but is within about 8 m, it is necessary to install the pumping set in a shallow pit constructed adjacent to the well. The pit is lined with brick or stone masonry and provided with a staircase/ladder for easy access. In case the pumping water level is still deeper, it is necessary to install the pump in the well and the engine at the ground surface or in a

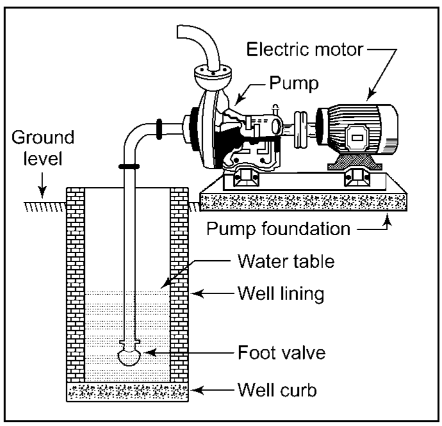

Fig. 10.16 Typical installation of an electric motor-driven horizontal centrifugal pump in a shallow open well where the pumping water level is within 6.5 m from ground surface

shallow pit, and provide a flat belt drive to transmit power from the engine to the pump. Suitably sized pulleys have to be provided on the shafts of the pump and the prime mover. In case of electric-motor driven pumps, the entire unit should be installed on a platform built inside the well (Fig. 10.17).

Installation of Centrifugal Pumps in Deep Open Wells

Emlectric-Motor Driven Pumps Sets

In general, a horizontal centrifugal pump should be installed as close as possible to the water table, without submerging it in water. It is especially important to avoid submergence of electric motors.

Lined wells. In lined deep open wells, the pump set, including the motor coupled to it, can be installed close to the static water level (Fig. 10.17). The pumping set is installed on a firm cantilever foundation built just above maximum static water level. A ladder is provided for inspection and servicing. The delivery pipe of the pump is supported at one or more points, to prevent damage to the pump due to water hammering when the motor is switched off. At places where there are wide fluctuations in the water table between seasons, it may be necessary to change the location of the pump during the different seasons. In such cases, it will be necessary to construct two or more platforms in the well, the upper platform to be used during the period of high water table. The pumping set is lowered to the lower platform when the water table falls.

Partially lined wells. There may be situations when only the top section of the well is lined. The lower section is stable to retain the sides, but cannot provide a base for installing the pump. Under such situations, the pumping set is installed on a cage-frame supported on steel girders or wooden beams

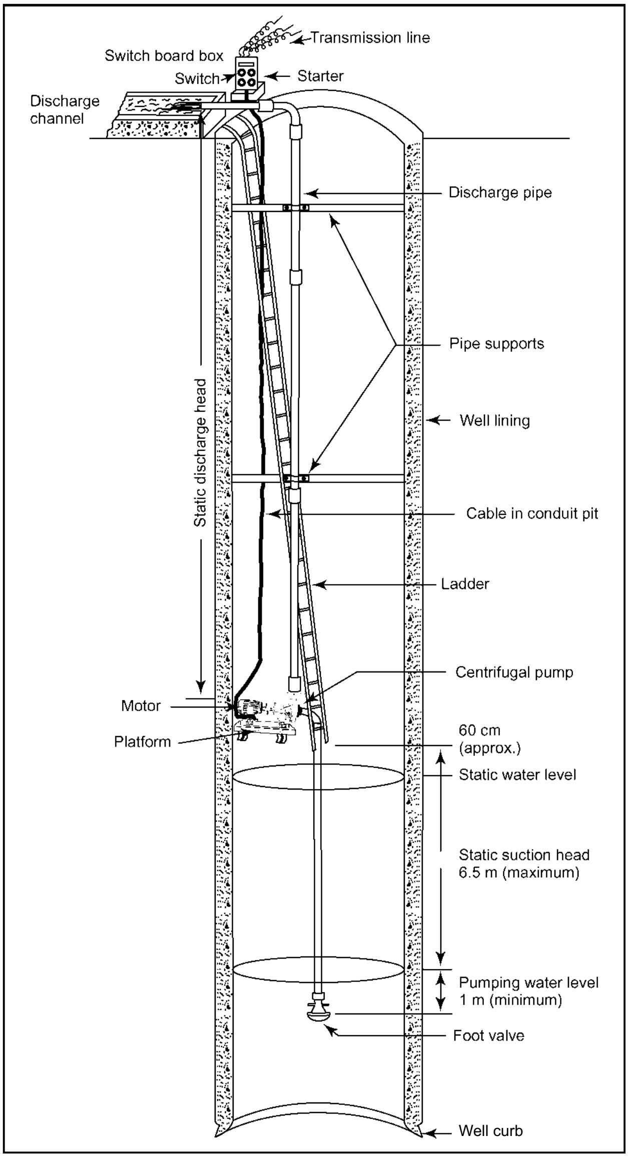

Fig. 10.17 Schematic sketch illustrating details of installation of a motor-driven centrifugal pump in a deep open well

installed at the top of the well (Fig.10.17(a). The beams are fixed on concrete/masonry foundations. The platform is usually made of wooden planks. Provision is made to raise or lower the cage-frame, in order to keep the pump within the maximum suction lift. The basic requirements of limiting suction lifts to 6.5 m and the submergence of foot valves to about 45 cm below the pumping water level are maintained in this case also.

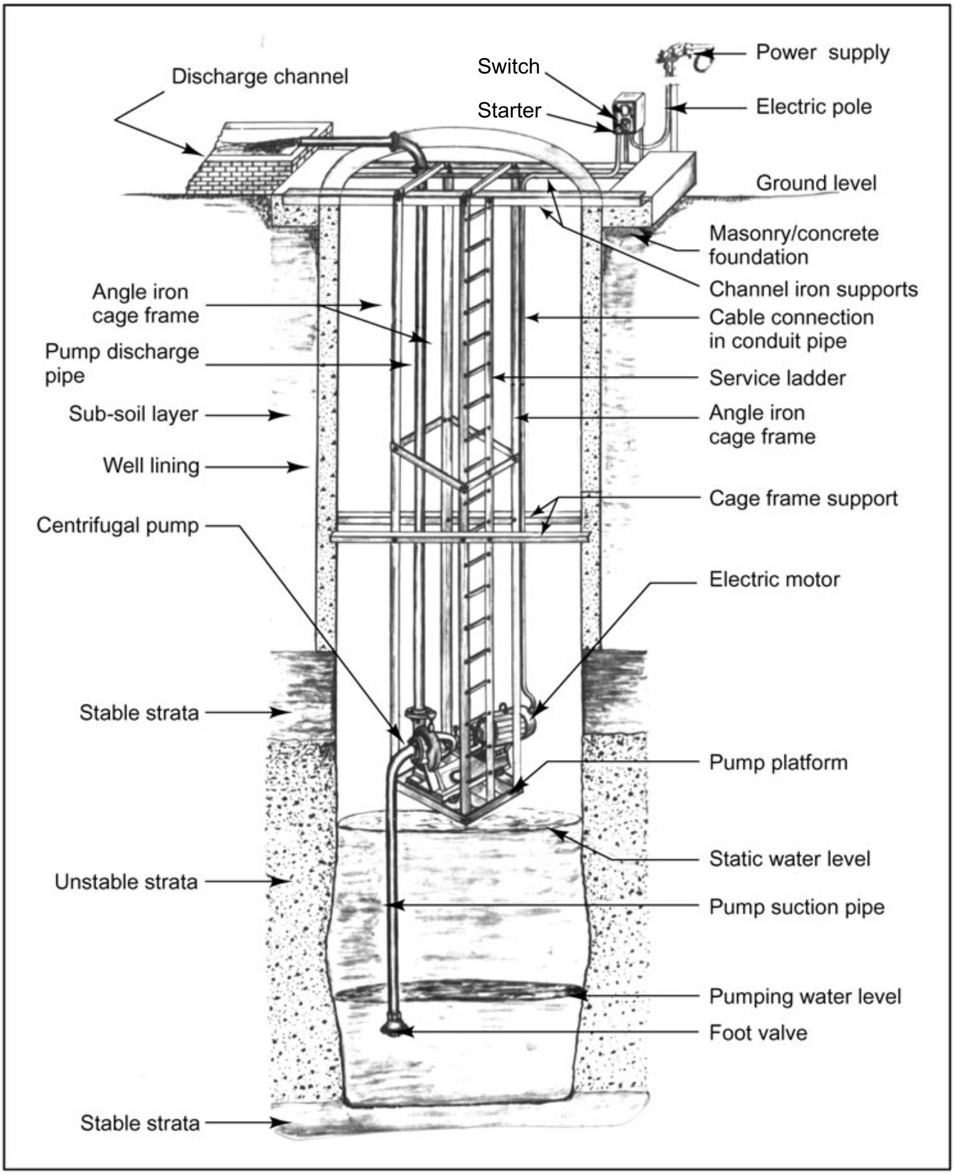

Fig. 10.17 (a) Installation of a centrifugal pump coupled to electric motor in a partially lined open well with unstable horizons below the lining, using a cage frame supported at the ground level. In case of highly fluctuating water tables between dry and wet seasons, provision should be made in the cage frame to raise or lower it, still keeping the pump within its permissible suction lift.

Floating pump. Often, it may be advantageous to use a floating pump in case an electric-motor driven pump set is required to operate under fluctuating water table situations in deep well. Figures 10.18 and 10.19 present the details of construction of a floating pump set suitable for deep open wells. A diffuser-type vertical centrifugal pump close-coupled to a vertical electrical motor is mounted on a float. The pump suction remains submerged in water. The motor-pump unit floats on the water surface in the well.

The electric motor is made waterproof by coating it with a special resin to avoid any damage even if it gets submerged accidentally. However, under such situations, the motor should be taken out immediately and the windings dried so as to bring the winding insulation above 5 megohms, as obtained through an insulation test with a Meger.

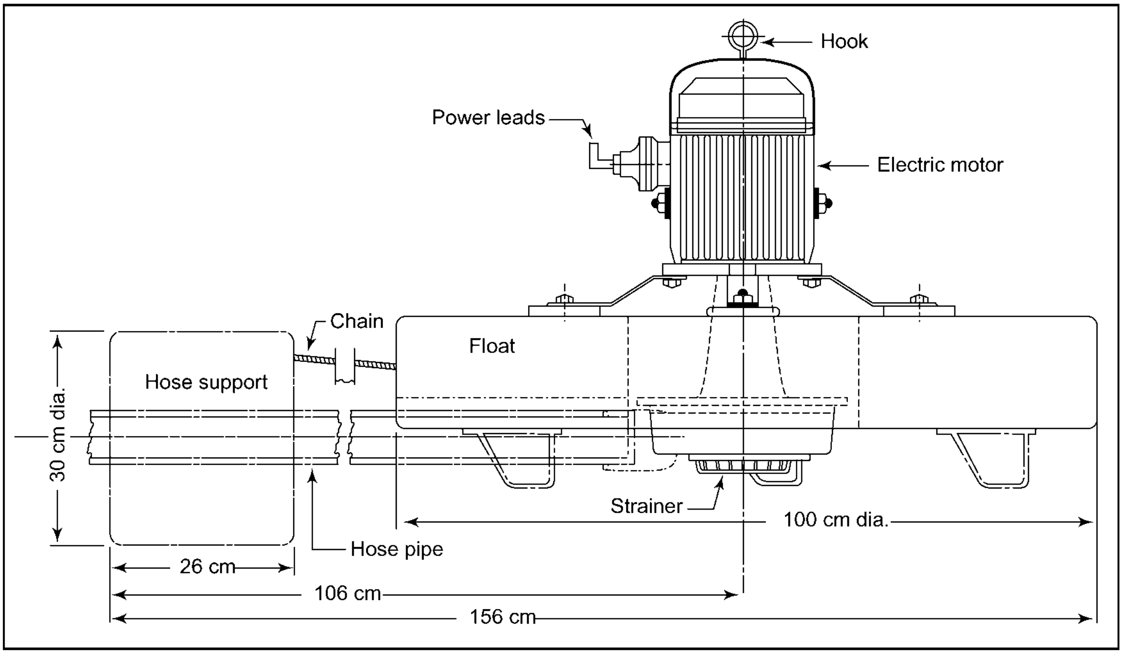

Fig. 10.18 View of a pumping set, float ring and hose support of a vertical centrifugal pump close-coupled to an electric motor
Courtesy: Kirloskar Bros. Ltd., Dewas, (Anon., 1962)

Figure 10.19 presents the details of installation of a float pump in an open well. Before installing the pump, all obstacles which may create difficulty in the free up-and-down movement of the pumping set are removed from inside the well. A strong wooden beam or GI pipe is placed over the top of the well for mounting the operating unit for the pump. The operating unit consists of a steel chain, one end of which is fixed to the hook of the pumping set. A dead weight (usually a sand bag) is attached to the other end. The chain works on pulleys. The length of the waterproof electric cable and the hose pipe are determined on the basis of the extent of fluctuation in water levels, which may be anticipated during the year. In case of the delivery pipe, an additional 1.5 m of pipe is provided over and above the difference in elevation between the maximum static water level and the minimum pumping water level.

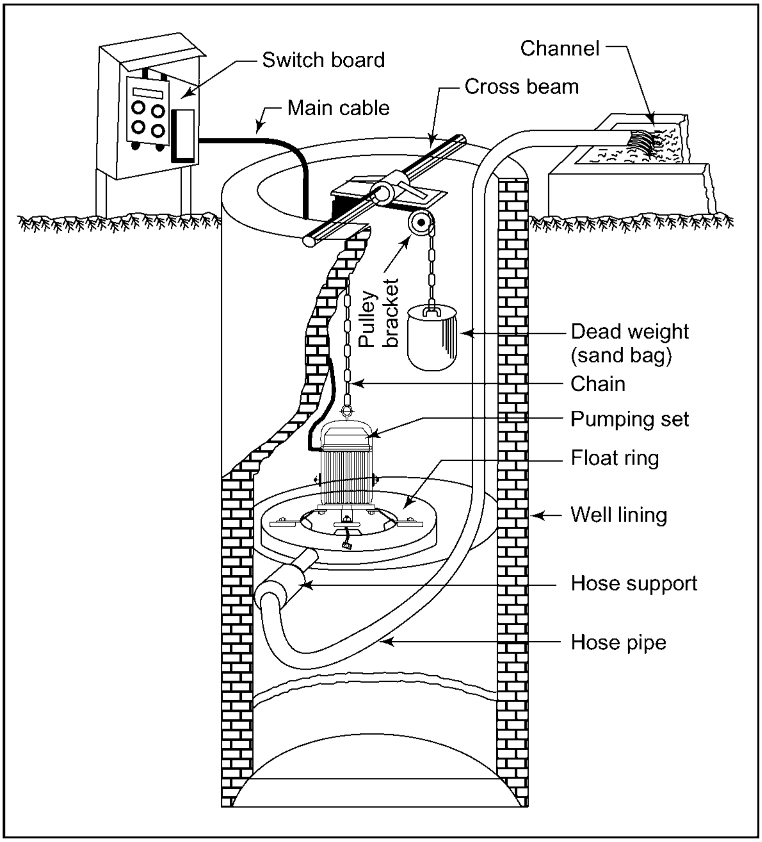

Fig. 10.19 Installation of a float pump in an open well
Adapted from: Kirloskar Brothers Ltd., Dewas (Anon., 1962)

Engine-driven Pump Set

In an engine-operated horizontal centrifugal pump, the engine is installed at the ground surface or in a shallow lined pit, (Fig. 10.19(a)) and the pump in the well close to the static water level. The pit is intended to reduce the distance of the belt drive. Power from the engine is transmitted to the pump with the help of a belt drive. When the distance between the engine and the pump is large, it is necessary to provide one or more counter shafts with pulleys to reduce the length of single belt. Care is taken to avoid a vertical belt drive. To reduce slippages, the belt should be as inclined as possible. In case of major fluctuations in the water table during wet and dry seasons, two or more platforms may be necessary for locating the pump close to the static water level.

The engine-driven centrifugal pump is not efficient when installed in deep open wells with belt drives. Long belt drives, used in transmitting power from the engine placed at the ground surface to the pump installed in the well, result in excessive power loss. The efficiency of engine-driven pumping sets installed in deep open wells can be increased substantially by replacing the belt drive with a vertical shaft drive to transmit power from the engine placed at the ground surface to the pump located close to the static water level in the well (Fig. 10.19(b)). The shaft is supported on standards provided with bearings at intervals of about 3 m. Short length quarter-twist belt drives are used to transmit power from the engine to the vertical shaft and from the shaft to the pump.

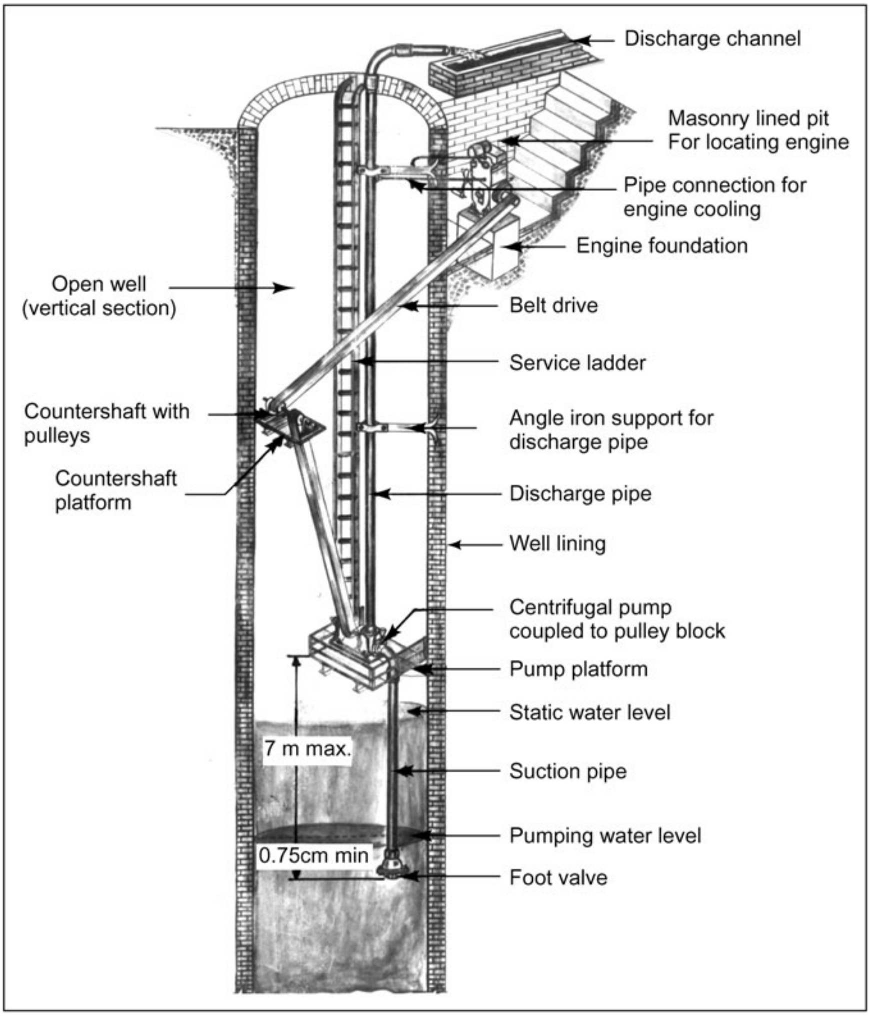

Fig. 10.19 (a) Installation of an engine-operated volute centrifugal pump, using a two-stage belt-drive in an open well. The pump is located within its suction limit while the engine is located in a lined pit below the ground surface much above the suction limit. In case of major fluctuations in water table in wet and dry seasons two or more platforms may be necessary for locating the pump close to the static water level to the pump to avoid excessive suction lifts. Note the inclined belt drive to provide higher efficiency in transmission of power.

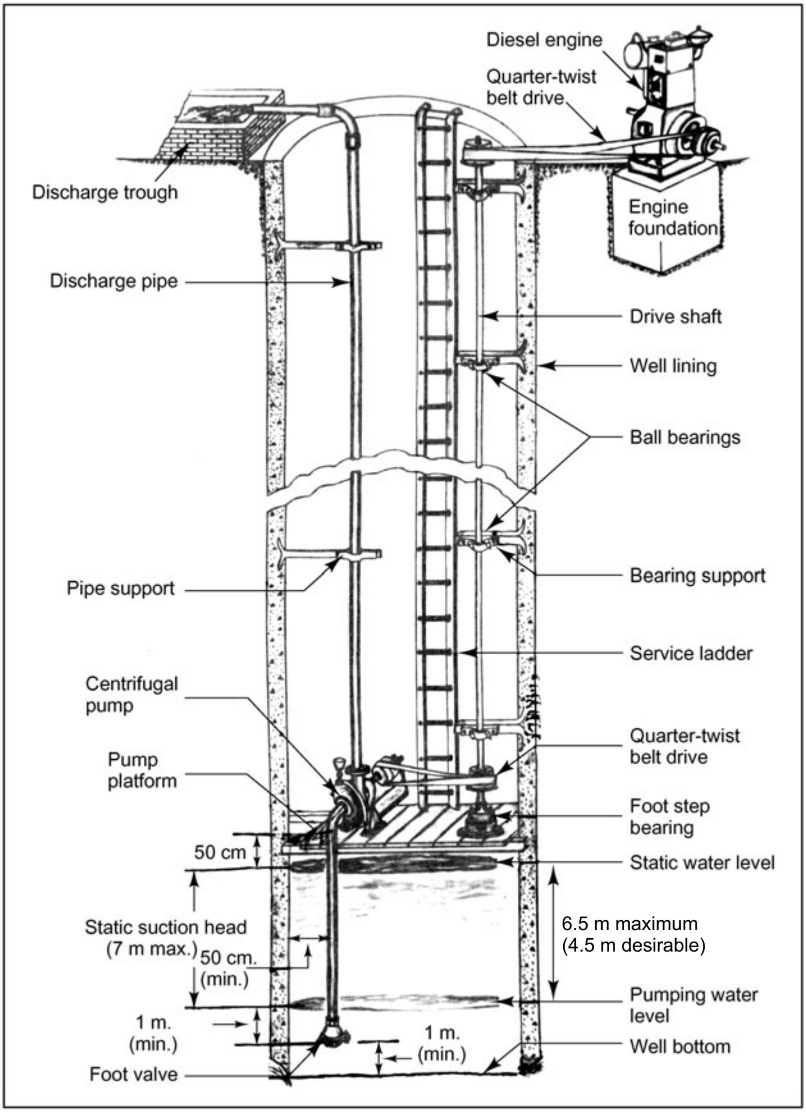

Fig. 10.19(b) Installation of a volute centrifugal pump in a deep open well using vertical shaft drive

10.2.5 Installation in Tube Wells

The procedures for the installation of horizontal centrifugal pumps to lift water from tube wells depend on the type of prime mover used and the depth of the water table below the ground level. In case of shallow tube wells where the total suction lift is limited to 4.5 m, the centrifugal pumps may be installed at the ground surface as direct coupled units (Fig.10.20a). A reflux valve is provided on the suction side of the centrifugal pump to help in priming. The pumping set may comprise a monoblock unit or a close-coupled unit. In case of engine-driven units, it is common practice to use a flat belt drive with a pulley head.

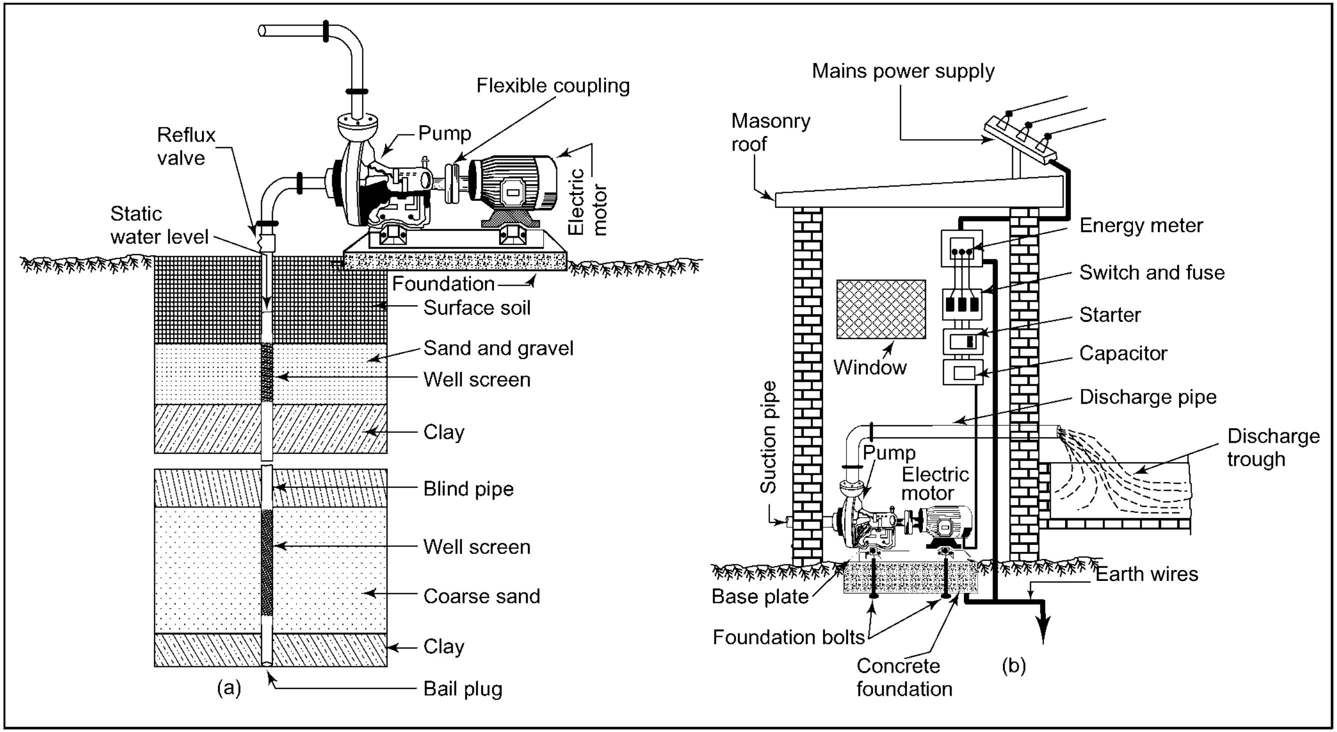

Fig. 10.20 Typical installation of electric motor driven horizontal centrifugal pumps in tube wells.
(a) Pumping set coupled directly to shallow tube well where suction lift is less than 6.5 m,
(b) Details of electrical connections and pump house

In case of tube wells where the suction lift is more than 4.5 m, the pump will have to be installed in a lined pit so that it remains as close to the water table as possible. However, the pumping set should always remain above the water table so as to avoid the submergence of the pump and the prime mover. In case of a fluctuating water table, the bottom of the lined pit is left without flooring, as the water table may rise above the bottom of the pit. Under such situations, two or more platforms are made for locating the pumping set during the different seasons.

Motor-driven centrifugal pumps can be installed conveniently in a lined pit (Fig. 10.21). However, pumps operated by diesel engines will have to be provided with suitable belt drives to transmit power from the engine placed at or near the ground surface to the pump installed in the pit. Vertical shaft drive similar to that described for open wells could be used in tube well pits also. When used to pump water from a tube well with a deep water table, because of the excessive depth, the construction of the lined pit becomes difficult and expensive.

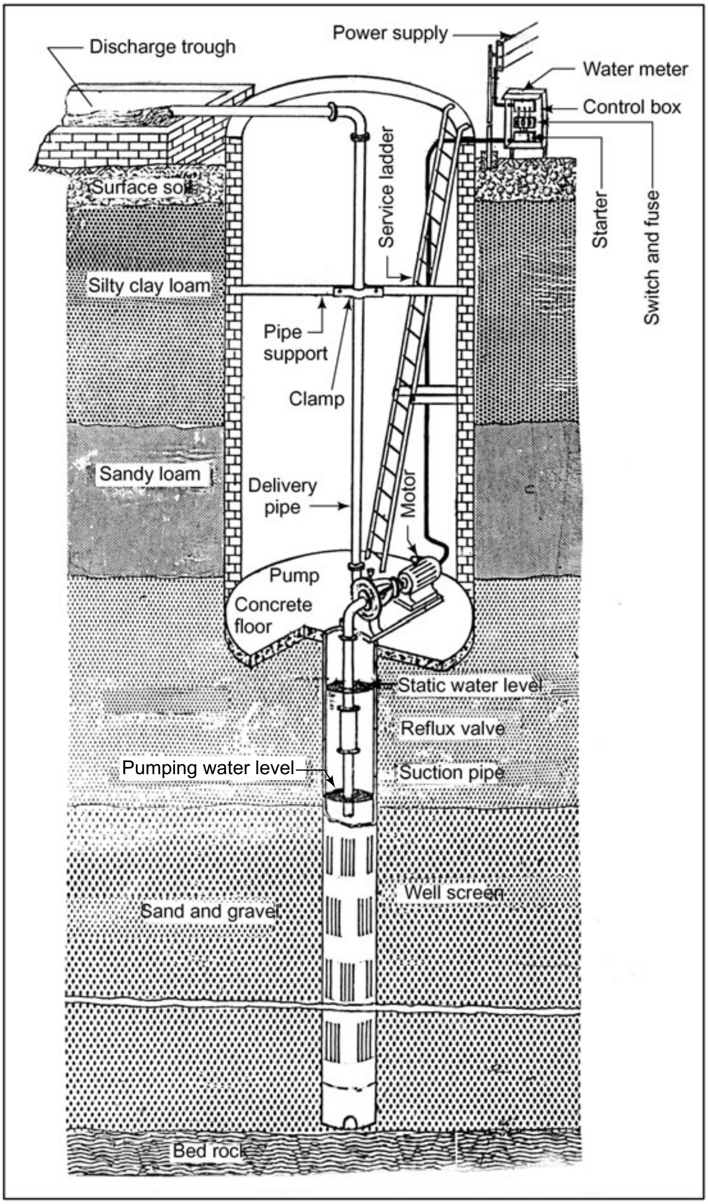

Fig. 10.21 Partially exposed view of a motor-driven volute centrifugal pump installed in a tube well provided with dry sump to keep the pump within its suction limits

In case of engine-operated units, the power in transmission is high. Another major limitation is the small suction lift (< 6 m) against which the pump can operate. It usually result in the under-utilization of the potential of the tube well under situations where the drawdown could be substantially larger. Thus, horizontal centrifugal pumps have very limited application in deep tube wells. Typical arrangement of electrical accessories and earthing in a pumping system installation is shown in Fig. 10.20b.

10.2.6 Portable Pumping Sets

Centrifugal pumps may be used as portable units for pumping from a battery of wells, one after the other, or from ponds, streams, canals or rivers. The essential requirement for a portable unit is that the pumping water level should not be deeper than about 6 m from the ground surface. Portable pumping sets are usually engine-driven. The pump and engine are mounted on a common base plate which is fixed to a trolley made of steel girders or wooden beams. The trolley is mounted on steel wheels or rubber tyred wheels. An ordinary bullock cart can also be used to mount the pumping set. In portable units, it is essential to ensure that the unit is located on a firm ground and maintained in a level position during operation.

Portable tractor-operated pumps could be mounted on the three-point linkage of the hydraulic system of the tractor (Fig. 10.22). The pump and speed change gear box are mounted on a mild steel frame. Flexible pipes are used for the suction line.

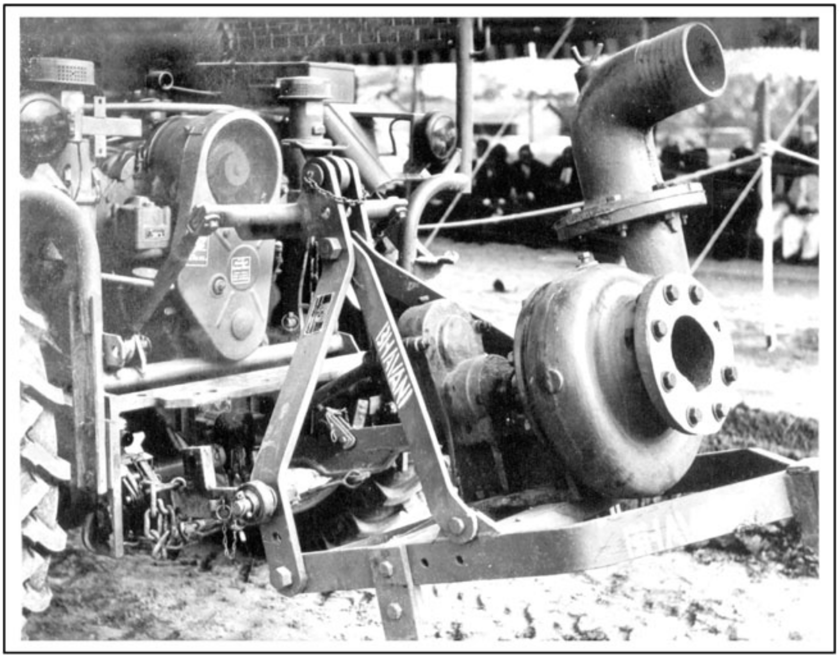

Fig. 10.22 A centrifugal pump mounted on the 3-point linkage of the hydraulic system of a tractor

10.2.7 Major Factors Influencing Wastage of Energy in Centrifugal Pump Installations

Field studies conducted at the Agricultural Universities at Ludhiana and Pantnagar and the Institute of Cooperative Management, Ahmedabad, have revealed that a majority of the centrifugal pumps in India are operating at very low efficiencies. Table 10.6 presents the results of studies conducted at the Punjab Agricultural University, Ludhiana.

TABLE 10.6 Overall Efficiency of Electric Pumping Sets in Punjab

Efficiency range	% of pumping sets
25.8 to less than 40%	31
40 to less than 50%	36
50 to less than 58%	33

Source: Thaman *et al*. (1982)

Investigations on the efficiency of pumping sets in the Terrai region of Uttar Pradesh, conducted by the Agricultural University, Pantnagar, revealed that the overall efficiency of pumping sets installed in fields in the Nainital district was 36 percent (Ram, *et al*. 1982), as compared to a acceptable minimum efficiency of 50 per cent.

The studies have shown that poor care and maintenance, excessive suction lift, improper selection and inferior quality of centrifugal pumps and wrong selection of ancillary equipment such as pipes, bends and foot valves are often the major factors leading to low efficiencies in pumps. The following are the major defects causing over-consumption of fuel or electrical energy in pump sets:

1. Wrong foot valve/reflux valve and strainer units, causing high frictional losses and reduced discharges
2. Undersized suction and/or delivery pipes
3. Unnecessary height of delivery pipe and/or too long suction pipes
4. Non-matching of pump with pumping head and discharge required
5. Oversized (Fig. 10.23) or undersized prime movers
6. Inferior quality of oil engines, with high specific fuel consumption
7. Over-cooling of oil engines
8. Non-replacement of certain vital compo-nents of oil engines which get worn or damaged, such as: (a) piston rings, (b) liner and piston, (c) fuel injector, (d) bearings, and (e) leaky valves
9. Low speed of pump due to the engine not working at the rated speed
10. Losses in power transmission from the prime mover to the pump in belt-driven units
11. Use of electric motors/engines with low efficiency
12. Use of oversized electric motors. i.e. under-loading of motor which reduces the power factor of the motor and hence the efficiency or use of oversized engines like tractors to operate a small pump (Fig. 10.23)
13. Use of inferior quality pipes and or wrong pipe fittings (Proper pipe fittings are shown in Fig. 10.24)
14. Non-replacement of worn-out bearings of pumps and electric motors and absence of periodic oiling and greasing of bearings
15. Excessive suction lift
16. Non-availability of information on drawdown-discharge characteristic of wells
17. Non-matching of pump characteristics with those of well characteristics
18. Use of suction and delivery pipes with excessive friction
19. Leaky joints in the suction/delivery pipeline
20. Too-tight gland packing, clogging of impeller/foot valve and improper bearings

Fig. 10.23 A medium horse power tractor operating a volute centrifugal pump installed to lift water from a shallow tube well. It is an example of using a high power unit for a small load, resulting in heavy loss in mechanical efficency of the power unit.

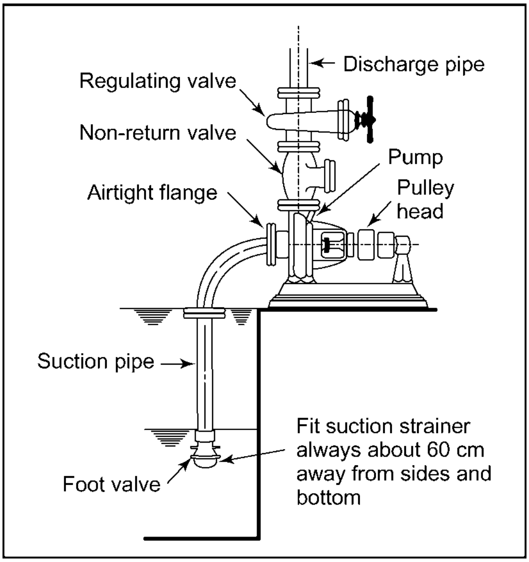

Fig. 10.24 Correct arrangement of suction piping and valves on the discharge side of a centrifugal pump. The valves on the delivery side are necessary only when pumping under high head

Foot Valves

Field studies of pump sets operated by the farmers of Gujarat State have indicated that more than 95 per cent of the farmers used inefficient foot valves with their pump sets (Patel, 1980). Such foot-valves create additional frictional head which leads to wastage of energy in the pump sets. It was estimated that if such high resistance foot valves were replaced by low resistance foot valves at least 10 per cent of the energy used in the agricultural pumps could have been saved.

Most of the foot valves available in the market and generally purchased by the farmers offered high resistance to flow of water. High suction heads increase the load on the prime-mover and reduce the efficiency of the pump. To keep the head loss to a minimum value, the foot valve should allow full bore flow of water and has total straining area equal to 3 times cross-sectional area of suction pipe.

Location of the Foot Valve

The foot valve should not be located in the vicinity of incoming streams and no whirl pools should be formed by its side. Air should not churn into the pumped liquid due to the agitated state of water around the foot valve. It should be made sure that there is sufficient space on all sides of the foot valve for water to flow freely. The foot valve should not be installed close to the bottom of the pump. This is essential to prevent the strainer holes from being choked up by mud and other material accumulated at the bottom of the pump.

Reflux Valves

It has been observed that the reflux valves available in the market vary greatly in standard and quality. Poor quality reflux valves result in excessive head loss due to friction and low efficiency due to restrictions in the flow path of water. Studies on the evaluation of commercially available reflux valves have indicated that some of the reflux valves caused excessive head loss (Kaushal *et al*. 1986). To keep the head loss to a minimum value the reflux valve should be smooth from inside and valve flap should open fully without obstructing the path of flow of water.

Piping System

The piping system of a pumping set consists of (a) a suction pipe with foot valve or reflux valve, and (b) delivery pipe. The National Bank for Agriculture and Rural Development (NABARD) and the Bureau of Indian Standards (BIS) have specified that the average velocity of water in the suction pipe should not be more than 1.5 m/s. In the delivery pipe, it should not exceed 2 m/s. To the extent possible, elbows, bends, tees and reducers should be avoided. At pipe corners, instead of sharp bends (elbows), long-radius bends should be used. The suction line should be as straight and short as possible. Sudden enlargements and reductions of pipe sections should be avoided as far as possible.

The material of the pipe influences the pipe friction substantially. For instance, the use of rigid PVC pipes in place of GI pipes can make an appreciable difference in the energy consumption of pumping sets.

Pipe Joint

Pipe joints, especially those on the suction side, should be absolutely air-tight. Any air leakage on the suction side will impair the vacuum and vitiate the pump performance. When screwed pipes are used, white lead and hemp string should be employed for making the joints. For flanged pipes, it should be ensured that the flanges are not bent and suitable rubber gaskets are inserted between the flanges.

Loss of Energy in Power Transmission System

The mechanical power developed in the diesel engine or electric motor has to be transmitted to the pump without much loss in the transmission system. The following are the common defects in power transmission system:

1. Use of belts and pulleys for transmission of power where monoblock pump sets are suitable and feasible
2. Use of vertical belt drives
3. Use of narrow belt, which elongate while in tension
4. Slippage of belts
5. Too many joints in flat belts
6. Misalignment of shaft coupling
7. Belts made from used truck tyres which elongate during use

10.3 CENTRIFUGAL PUMP OPERATION

Proper operation procedures result in trouble free working of a centrifugal pump set. Prior to starting the pump for the first time, special attention is paid to the following points:

1. Check the alignment of the pump. If there is any misalignment, the same is rectified as per the procedure laid down in Sec. 10.2.3.
2. Make sure that the engine or motor will drive the pump in the direction indicated on the pump body. (To determine the direction of rotation of a horizontal centrifugal pump, the operator should stand at the end of the prime mover, facing the pump. If the top of the shaft revolves from left to right, the pump is said to rotate clockwise).
3. Make sure that the gland packing is lightly and evenly adjusted and the pump shaft revolves freely when turned by hand.
4. Check the air-tightness of the suction pipe and any leakage in the foot valve/reflux valve.
5. Check the suction and delivery pipes to see that all the joints are tight and will not leak.
6. Ensure that the lubrication schedule of the engine/motor is followed strictly. Wherever possible, the prime mover should be operated independent of the pump to see that it is in good operating condition.
7. Attend to the lubricant requirements of the pump. In the case of most horizontal centrifugal pumps, ball bearings are fitted, for which no initial attention is required as they are properly lubricated before leaving the factory.

10.3.1 Starting, Running and Stopping of the Pump

Starting

The pump must not be started without being primed. Priming is done by filling the pump casing and suction pipe completely with water, thus ensuring that all the air contained in the pump casing and suction pipe is made to escape. The filling of water can be done through a funnel attached to the priming connection of the pump. While filling water, the air-release valve is kept open to permit the air to escape from the pump section. Spilling of water through the air-release valve is an indication that priming has been completed. However, if the foot valve/reflux valve is leak-proof, the discharge line remains full of water and, hence, there is no need for priming. Similarly, when the pump is installed below the level of the source of supply, the water flows into it under a positive head and no priming is needed. The delivery valve, if provided, is kept closed while starting the pump. After the prime mover is started, the delivery valve is slowly opened. If the delivery pressure of the pump does not increase continuously as the speed increases, the pump should be stopped and primed again carefully. During operation, the pump should work smoothly and the prime mover should not get overloaded.

Due to its simple construction, the centrifugal pump requires practically no attention while running. Proper lubrication of the bearing and adjustment of the glands are usually the only points which require the attention of the operator. The centrifugal pump must be stopped promptly if no liquid is being pumped. Running a pump dry will result in excessive wear of moving parts which depend on water for lubrication. Sluice valves, when provided, are kept closed at the time of starting. This will allow the motor or engine to be started without load. When the pump reaches its full speed, the sluice valve is opened gradually until the desired quantity of water is delivered. Care is taken not to run the pump for a long period with the sluice valve closed, as this may overheat the pump.

Stopping

No special precaution is needed while stopping small and medium-sized pumps. However, in case of high-head pumps, care should be taken to prevent damage of the pump due to water hammering. In high-head installations, a non-return valve is provided at the delivery end to prevent water hammering. In case of installations which are provided with a sluice valve only, the valve is closed before stopping the pump.

10.4 MAINTENANCE AND TROUBLE-SHOOTING

Proper maintenance of a centrifugal pump is important to ensure its trouble-free and long service. The maintenance operations of a centrifugal pump include (i) routine preventive maintenance, and (ii) overhaul or repair operations.

10.4.1 Routine Maintenance

The operating conditions of pumps vary widely and so do the maintenance requirements. The performance of the pump should be observed daily. Any abnormality in operation should be taken care of promptly. This refers mainly to any change in the sound of running, undesired leakage in the stuffing box, abnormal change in voltage and current, and temperature. The alignment of the pump unit should be checked occasionally. Bearings requiring lubrication, if any, should be attended to regularly.

Half-yearly Maintenance

At least once in six months, the shaft packing is checked by observing the leakage from it. Generally, a leak of 15–30 drops of liquid per minute from the stuffing box is desirable. If the leakage from the stuffing box is excessive or the packing is worn, the entire packing in the box will have to be replaced. Replacing just a ring or two will not result in an effective sealing. While overhauling the stuffing box, all the old packing rings are removed and the interior of the stuffing box cleaned thoroughly. The shaft and shaft sleeve surface are properly cleaned before inserting the packing rings. There should not be any burrs or scores on the working surface. If the shaft sleeve is badly worn or scored, it is replaced. Similarly, the straightness of the shaft is ensured.

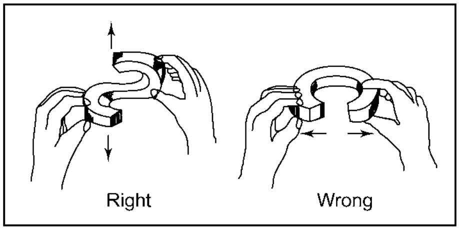

Fig. 10.25 Jointing procedure for succeeding packing rings
Courtesy: Kirloskar Brothers Ltd., Pune (Anon., 1962)

The radial clearance between the shaft and the stuffing-box bore is measured for determining the size of a new gland packing to be provided. The packing should not be inserted in a spiral form. It is installed in individual rings (Fig. 10.25). The rings are carefully cut to the exact size by wrapping the packing around the shaft. The packing rings are fitted carefully, opening them radially until the ends are as wide apart as half the shaft diameter, then the ends are turned apart in an axial direction, until the rings slide over the shaft. Then each ring is pushed into the stuffing box, inserting the joint first. It should be ensured that the joints of succeeding packing rings are staggered. This is followed by assembling the gland ring and tightening the nuts by hands or using a spanner. When the pump is in operation, the nuts are again adjusted to achieve the desired leakage from the stuffing box.

The pumps installed on cavity wells need half-yearly checking. Many a times, pieces of stones or gravel get into the pump casing due to over pumping which results in decrease of discharge. In such situations the pump is opened and cleaned.

10.4.2 Overhauling of Pumps

Centrifugal pumps have two basic types of parts—rotating and stationary. Rotating parts include the impeller, shaft, wearing rings, shaft sleeves, and bearings. Stationary parts include the casing with the suction and discharge flanges, bearing housing and packing. Most overhaul work on centrifugal pumps is concerned with the rotating parts.

It is desirable that the pump is completely overhauled annually or once in two years. However, in many situations, the operating conditions do not permit annual shutdown periods for overhaul. In such cases, over-hauling is done when it is absolutely essential, on the basis of pump performance and symptoms indicating major trouble. The following situations call for a shutdown of the pumping plant for trouble-shooting, repair and possible overhaul:

1. Fall-off in pump performance
2. Excessive noise during pump operation
3. Excessive vibration of pump
4. Symptoms of corrosion or erosion trouble

Dismantling of Centrifugal Pumps

The pump has to be dismantled for overhauling. As already discussed, there are different types of horizontal centrifugal pumps like monoblock or close-coupled pumps, belt-driven pumps and directly-coupled pumps. The dismantling and reassembling procedure of a belt-driven pump is discussed in this section. However, the basic principles are the same, irrespective of the type of centrifugal pump.

The pump is first disconnected from the piping system (in case the pump is directly coupled, it is uncoupled by removing the coupling bolts and rubber bushes). The various steps involved in dismantling a belt-driven pump are listed below:

1. Remove the inlet and outlet flanges
2. Remove the bearing cap by removing the bolts holding it
3. Remove the grease cup and bearing lock nut
4. Remove the pedestal and take out the ball bearing, using a bearing puller
5. Remove the belt shifter
6. Remove the nuts and bolts joining the casings and remove the casing slowly, taking care not to damage the impeller and casing rings
7. Remove the impeller nut
8. Dismantle the rotating unit and remove the impeller slowly by hammering back the shaft gently, using a wooden block
9. Remove the impeller from the rotating unit
10. Remove the pulleys using a pulley puller
11. Dismantle the stuffing box

Procedures in the overhauling of various components of centrifugal pumps are described below:

Overhauling of Impellers

As soon as the impeller is removed from a pump, its eye, vanes, shrouds, wearing rings, passages and hubs are checked. Corrosion, cavitation and erosion are generally accompanied by the wearing of the impeller vane surfaces. When the corrosion or erosion is severe, the thinned sections may have holes in them, or may warp or deflect. If cavitation is severe, it may be necessary to change the suction conditions or fit a new impeller which is suitable for the existing suction situations.

The impeller has to be thoroughly cleaned before inspection. Scale, coke and other deposits can be removed by chemical cleaning or sand blasting. However, care must be taken that the impeller material is not damaged in the process. While it is possible to recondition a worn or corroded impeller, it is often better to replace it with a new one which is suitably protected to resist wear or corrosion.

Balancing of Impeller

Many a times, the impeller is badly worn or corroded and vibrate excessively. Such an impeller needs rebalancement. Under such conditions, the impeller and shaft should be returned to the manufacturer or sent to a standard workshop for rebalancing. Balancing of an impeller can be checked by pressing it on an arbor, the ends of which rest on two parallel and level knife-edges, by hand. If the impeller is out of balance, it will turn and come to rest with its heavy side down. If found unbalanced, the metal is removed from the heavy side. However, drilling holes on the heavy side is undesirable. A cut could be taken from the shroud, being deepest at the rim. However, in case of semi-open impeller, where the design may not permit removal of metal from the shroud, the metal may be removed from the underside of the vane of the impeller.

Repair of Shaft

The shaft is checked for bending with a dial gauge, by turning the shaft between lathe centres. If the shaft is badly bent, it should be returned to the manufacturer for straightening as, normally, such facilities are not available locally. Reconditioning of the shaft will require welding or metalling, followed by rough finishing cuts. The final finishing is done by filing to the desired size. Fine emery paper (0 size) is used to give a smooth finish.

Replacing of Wearing Rings

Proper clearance of the wearing ring is important. An increase in clearance results in leakage of the liquid past the rings, which reduces the efficiency of the pump. The wearing rings are installed to take the wear resulting from the rotation of the impeller, grit or any other cause. If the wearing rings are worn out and the clearance increases, they will have to be replaced.

Repair of Shaft Sleeves

The shaft sleeves often get worn out when packed too tightly. They can be reconditioned by welding or metallizing, followed by a rough finishing cut, leaving enough metal for filing and lapping to the final size. Finishing is done with a fine emery cloth. Where the wear is excessive, the shaft sleeves will have to be replaced.

Repair of Non-stationary Components

Usually, the repair of non-stationary components is negligible. The bed plate is kept clean of grease and oil at regular intervals. The joints and piping are checked regularly for leakage, etc. The foundations are kept clean. The cracks in foundations, if any, are repaired in time. The surface of the casing may require painting to safeguard against rusting.

Reassembling the Parts of a Centrifugal Pump

After overhauling, the pump is reassembled. The procedure of reassembling is more or less the reverse of dismantling. The following are the major steps involved in reassembling a pump with pulley:

1. Mount the pulleys on the shaft
2. Mount the casing and stuffing box bushes on the shaft
3. Gently mount the impeller on the shaft
4. Insert the impeller key carefully
5. Adjust the impeller at its correct position and tighten the impeller unit
6. Insert the gasket and grease it properly
7. Mount the casing by tightening its nuts and bolts
8. Insert the belt shifter at its correct position
9. Insert the shaft sleeve and tighten it properly
10. Mount the pedestal and align it properly by inserting the desired packing (shims)

11. Mount the ball bearing, on hand press, and tighten the bearing locking nut. Do not hammer the ball bearing
12. Mount the bearing cap

10.4.3 Trouble-Shooting in Centrifugal Pumps

Troubles in centrifugal pump may be grouped into three: mechanical, hydraulic and driver related (Butts, 2004). Mechanical troubles include breakage of the coupling or shaft. These are easily traceable and can be attended to promptly. However, hydraulic troubles like failure to deliver water, reduction in discharge and overloading of the prime mover are more difficult to rectify. The principal troubles encountered in a centrifugal pump are discussed below:

No Liquid Delivered

The trouble could be attributed to the following factors:

(i) Lack of prime

This can be rectified easily. The pump and its suction pipe are filled with water. While filling the pump and pipe, the air-release valve is kept open till clear bubble-free water flows out of it. The pump is started after closing the valve.

(ii) Speed of the electric motor/engine too low

The speed of the motor driving the pump may be low because of low voltage. Hence, it is necessary to check the voltage. Sometimes the motor may have an open phase which causes it to run at a speed lower than its rated speed. In case of an engine-driven pump, the fuel-supply and governor settings are to be checked.

(iii) Discharge head too high

The principal reasons are a partially closed sluice valve on the delivery side and blocking of the suction or delivery pipe with solids entrained in water.

(iv) Suction lift too high

This may be due to the clogging of the pump inlet with mud, gravel or some other obstruction. The other reason could be a broken disc or a clogged strainer of the foot valve. In case the pump is being started for the first time, the actual suction lift could be excessive. In such a case, the pump is to be lowered so that the total suction lift is within 6.5 m (preferably within 4.5 m to ensure efficient operation).

(v) Impeller plugged

In case of cavity wells, solids in the water may accumulate in the impeller. This may block the pump either completely or partially. Under such situations, the pump casing should be opened and all parts of the impeller cleaned periodically.

(vi) Vapour lock in suction line

Vapour pockets may develop in the pump suction line due to excessive suction head and inadequate submergence of the foot valve. The possible remedies include lowering the pump and increasing the submergence of the foot valve below the pumping water level.

Not Enough Water Delivered

This is a common trouble experienced by farmers. The various reasons and remedies suggested in case no liquid is delivered are applicable in this case also. The additional causes are discussed below:

(i) Air leaks

Air leakage may take place either in the stuffing box or in the suction pipe. As already indicated, the stuffing box should leak a small amount of water during pump operation. First of all, one should check for the desired leakage by making suitable adjustments. If this adjustment fails to give the desired results, the pump should be stopped and the gland packing checked for damage. A damaged gland packing should be replaced by a new one. The leakage from the stuffing box is again checked. If, even after replacement of the gland packing, the defect is not removed, the suction line will have to be checked for air leakage. The flanges and screwed joints are tightened first. In case the leakage is not traceable, the same can be located by using a flame or a lighted match-stick. The flame, if held close to the pipe and flanges, will be drawn towards any leaks.

(i) Worn wearing rings

The discharge of a pump is reduced if the wearing rings are worn. Therefore the rings should be checked and, if found worn, replaced.

(ii) Damaged impeller

Damaged impeller vanes result in reduced discharge. The impeller should be inspected by removing the casing. If the vanes or other parts of an impeller are found worn or damaged, they should be replaced by new ones.

(iii) Defective foot valve

The total area of the openings in the strainer of a foot valve should be about 3 times the cross-sectional area of the suction pipe. Any reduction in the open area results in heavy friction losses and reduced pump discharge. Similarly, the flap valve in the valve body should open fully.

(iv) Worn gaskets

All gaskets should be replaced during an overhaul. The bolts at the joints where the gasket are inserted should be tightened uniformly, using a torque wrench if possible.

(v) Impeller eye too small

The capacity of a pump is a function of the diameter of the impeller eye. Therefore, incorrect choice of a pump or moving it from one bore to the other may result in this trouble. The only remedy in such a case is the replacement of the pump with a properly selected one.

Pump Losses Prime after Starting

The loss of priming after starting a pump may be due to incomplete priming, air leaks in the gland packing or in the suction pipe, air or vapour pockets in the suction line, insufficient submergence of the inlet, and low net positive suction head. The remedies already suggested for these cases are applicable in this situation also.

Overloading of Motor/Engine

The following are the main causes for overloading of the motor/engine.

(i) Low discharge head

If the head against which the pump is operating is too low, the pump delivers more water. This results in overloading of the prime mover. The main cause is improper selection of the pump.

(ii) Packing too tight

In this case, the pressure on the gland packing is released and the packing retightened suitably. Simultaneously, leakage from the gland packing should also be checked. It should be within the recommended range.

(iii) Bent shaft

The average runout of the shaft should not be more than 0.075 mm and 0.150 mm, for high speed and low speed pumps, respectively. The shaft deflection should be checked with a dial gauge by turning the shaft between lathe centres. If the shaft is found damaged, it should be replaced.

(iv) Distorted casing

Many a time, the casing gets distorted because of poorly aligned suction and discharge piping. This results in excessive friction between the impeller and casing. The piping and the alignment of the prime mover should be checked. The wearing rings should also be checked and replaced, if found damaged.

(v) Pump speed too high

Even a slight increase in pump speed results in a significant increase in power input, as it increases as the cube of the speed. If the pump speed is too high, the line voltage of motor-driven pumps and the governor on engine-driven units should be checked. Simultaneously, the speed of the prime mover should be checked and corrected, if necessary.

Overheating of Stuffing Box

The various reasons for overheating of the stuffing box are too tight a packing, insufficient packing, inadequate lubrication, wrong grading of gland packing, and incorrect installation of the gland packing. The packing should be installed as explained in Sec. 10.4.1.

Excessive Vibrations

Excessive vibrations in pumps are mainly due to misalignment, worn or loose bearings, unbalanced rotor, plugged or damaged impeller, bent shaft, or defective piping and foundations. Another cause of vibration is vapour pockets in the suction line.

Overheating of Bearings

Overheating of bearings is mainly because of defective lubrication, such as too little lubrication, poor or wrong grade of lubricant or dirt in the bearing, or too-tight bearing and misalignment of shafts.

Rapid Wear of Bearings

The possible reasons causing this trouble are misalignment of shafts, bent shafts, vibrations, excessive thrust from mechanical failure inside the pump, lack of lubrication, dirt and moisture in the lubricant, and wrong installation of bearings.

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PROBLEMS

10.1 A single-suction radial pump, with a discharge capacity of 0.03 m^3/s, develops a head of 25 m. If $D_H = 4$ cm, $C_0 = 3.75$ m/s, $C_{m1} = 4$ m/s, $C_{m2} = 3.75$ m/s, $\in_1 = 0.90$, $\in_2 = 0.88$, $\phi = 1.04$, leakage loss = 2% and $n = 1450$ rpm, determine the approximate values of D_0, D_1, D_2, β_1, β_2, b_1 and b_2.

Ans. $D_0 = 10$ cm, $D_1 = 10$ cm, $D_2 = 30$ cm, $\beta_1 = 27°, 28'$, $\beta_2 = 30°$, $b_1 = 2.6$ cm, $b_2 = 1$ cm

10.2 A double-suction radial pump, with a discharge capacity of 0.04 m^3/s, operates at a head of 20 m. If $n = 1450$ rpm, $C_0 = 3.05$ m/s, $C_{m1} = 3.20$ m/s, $C_{m2} = 3.00$ m/s, leakage loss = 2%, $\in_1 = 0.92$, $\in_2 = 0.90$ and $\phi = 1.05$, determine the approximate values of D_0, D_1, D_2, β_1, β_2, b_1 and b_2.

Ans. $D_0 = 8$ cm, $D_1 = 8$ cm, $D_2 = 27$ cm, $\beta_1 = 27° 47'$, $\beta_2 = 30°$ $b_1 = 2.7$ cm per side, $b_2 = 1.8$ cm

10.3 Determine the approximate tongue angle θ_t of a volute of a centrifugal pump, $r_1 = 30$ cm, $\alpha_2 = 20°$.

Ans. $\theta_t = 12°43'$

SHORT QUESTIONS

I. State True (T) or False (F).

1. In a horizontal pipe, the decrease in velocity results in an increase in pressure.
2. The absolute fluid velocity in an impeller is taken with respect to the impeller.
3. The absolute velocity is always equal to the vector sum of the relative velocity and the peripheral velocity of the impeller.
4. Velocity triangles are used to study the components of flow through an impeller.

5. The water coming out of the rotating impeller tends to rotate in the direction of the rotation of impeller.
6. Pumps of same specific speed but of different sizes are considered to be geometrically similar.
7. With increase in specific speed, the ratio of the impeller outlet diameter to inlet or eye diameter increases.
8. For a multi-stage pump, the specific speed is calculated on the basis of the head per stage.
9. Generally, lower the specific speed, higher the head that can be developed per stage by the pump.
10. In double suction pump, the specific speed is calculated on the basis of pump capacity.
11. The standard speed of electric motor is 1440 rpm or 2900 rpm.
12. For radial flow impellers, double curvature vanes are used.
13. In case of mixed and axial flow impellers several velocity triangles are drawn.
14. The number of vanes for low to medium specific speed pumps varies from 5 to 12.
15. A casing with diffusion vanes is more efficient than the volute type casing.
16. Large vane angles require less number of vanes to provide proper guidance to the liquid.
17. The cross-sectional area of volute gradually decreases from tongue to throat.
18. Before fixing the dimensions of the impeller, the shaft diameter must be approximated.
19. Euler's velocity triangles are drawn to design the impeller.
20. Specific speed is a dimensionless number.
21. An increase in suction lift lowers the efficiency of centrifugal pump.
22. The increase in excess of NPSHA over NPSHR results in decrease in pump discharge.
23. The weight of the foundation for centrifugal pump set should be equal to the weight of the pump set.
24. Flexible coupling does not takes care of misalignment of the shafts of the pump and the prime mover.
25. Shafts with axes concentric but not parallel results in angular misalignment.
26. Angular alignment can be checked by placing a straight edge across both the coupling rims, at the top, bottom and both sides.
27. On flat belt and V-belt drives, the tight side of the belt should be at the bottom.
28. The total straining area of the foot valve should be more than 2.5 times the cross-sectional area of suction pipe.
29. The average velocity of water in suction pipe should be more than 1.5 m/s.
30. The average velocity of water in delivery pipe should not exceed 2 m/s.
31. Too many joints in flat belt results in loss of energy in power transmission system.
32. No priming is required when the centrifugal pump is installed below the level of source of water supply.
33. Running a centrifugal pump for a long period with sluice valve closed, results in overheating of the pump.
34. Running the centrifugal pump dry results in excessive wear of stationary parts.
35. The size of new gland packing depends on the radial clearance between the shaft and the stuffing box bore.
36. The centrifugal pump installed on a cavity well needs more frequent checking in comparison to strainer tube well.
37. The capacity of a centrifugal pump is not a function of the diameter of the impeller eye.
38. Loss of priming after starting a centrifugal pump may be due to high NPSHA.

39. An increase in pump speed may results in overheating of the prime mover.
40. Incorrect installation of gland packing may results in overheating of stuffing box.

Ans. True: 1, 3, 4, 6, 8, 9, 11, 13, 14, 15, 18, 19, 20, 21, 24, 25, 27, 28, 30, 31, 32, 33, 35, 36, 39, 40.

II. Select the correct answer.

1. Velocity triangle is usually drawn on the
   (a) discharge ends of impeller vanes (b) eye of impeller
   (c) throat of volute (d) tongue of volute
2. In a multi-stage pump, the specific speed is calculated on the basis of
   (a) total head (b) head per stage
   (c) capacity per stage (d) head and capacity per stage
3. Single curvature or plain-curvature vanes are use for
   (a) mixed flow impeller (b) axial flow impeller
   (c) radial flow impeller (d) both radial and axial flow impeller
4. For a normal design the vane angle of the pump impeller varies from
   (a) 1.5° to 16.5° (b) 17.5° to 27.5°
   (c) 27.5° to 37.5° (d) 37.5° to 47.5°
5. The inlet velocity through the eye of the impeller is usually
   (a) more than velocity in the suction flange
   (b) less than the velocity in the suction flange
   (c) equal to the velocity in the suction flange
   (d) more than velocity of flow at the inlet
6. A machine that moves liquid is a/an
   (a) hydraulics (b) compressor
   (c) pump (d) pneumatics
7. Grouting helps primarily in preventing
   (a) lateral movement of pump base (b) shear failure
   (c) misalignment (d) differential settlement
8. Water hammer can be solved or greatly reduced by
   (a) installing solenoid valve (b) avoiding long, vertical rises in the pipe
   (c) avoiding long, horizontal runs of the pipe
   (d) installing reflux valve on suction pipe
9. The cement concrete used for the pump foundation usually has a mix ratio of
   (a) 1:1½:3 (b) 1:2:4
   (c) 1:3:6 (d) 1:4:8
10. Before installing new gland packing, the old packing should be
    (a) realigned (b) lubricated
    (c) sealed evenly (d) removed
11. What could cause a pump to start too frequently?
    (a) worn impeller (b) worn motor bearings
    (c) leaking foot valve (d) partially clogged impeller

12. To satisfy the vibration requirements, the weight of the foundation of a horizontal centrifugal pump should be at least
    (a) 1.5 times the weight of the pumping set
    (b) 2.5 times the weight of the pumping set
    (c) 3.5 times the weight of the pumping set
    (d) 4.5 times the weight of the pumping set
13. Loss of energy in power transmission will be more in
    (a) V-belt drive (b) horizontal belt drive
    (c) vertical belt drive (d) inclined belt drive
14. Running a centrifugal pump dry will results in excessive wear of
    (a) moving parts (b) stationary parts
    (c) reflux valve (d) foot valve
15. At the time of starting a pump set, the sluice valves, when provided are
    (a) kept closed (b) kept partially closed
    (c) kept open (d) removed
16. In high-head pumps, the damage to pump due to water hammering can be prevented by
    (a) keeping sluice valve open at the time of stopping
    (b) providing a non-return valve at the delivery end
    (c) providing a non-return valve at the suction end
    (d) providing a solenoid valve at the delivery end
17. The main cause for overloading of the motor/engine is
    (a) high discharge head (b) damaged impeller
    (c) low discharge head (d) too high suction lift
18. The loss of priming after starting a pump may be due to
    (a) low NPSHA (b) high NPSHA
    (c) low NPSHR (d) low speed of the prime mover
19. The proper way of balancing an unbalanced impeller is
    (a) to remove metal from the heavy side (b) to add metal to the light side
    (c) to drill hole on the heavy side (d) to trim the diameter of the impeller
20. The new gland packing in the stuffing box is inserted
    (a) in a spiral form (b) by keeping in line the joint of individual ring
    (c) by staggering individual ring (d) over the old packing

Ans. 1. (a) 2. (b) 3. (c) 4. (b) 5. (a) 6. (c) 7. (a) 8. (b)
9. (b) 10. (d) 11. (c) 12. (b) 13. (c) 14. (a) 15. (a) 16. (b)
17. (c) 18. (a) 19. (a) 20. (c)

11

Deep Well Turbine and Submersible Pumps

Deep well turbine and submersible pumps are diffuser-type vertical centrifugal pumps, specially adapted to pumping from tube wells. These pumps use a bowl, instead of a volute, to change the velocity head to pressure head. The pump bowl houses the impeller and guide vanes. The bowl assemblies are nearly always located beneath the water surface. Hence, deep well turbine and submersible pumps are adapted to seasonal fluctuations in water level in the well. They are also adapted to high lifts and have high efficiencies. They have, however, higher initial costs and are more difficult to install and repair, as compared to volute pumps.

11.1 VERTICAL TURBINE PUMPS

A vertical turbine pump is a vertical-axis centrifugal or mixed-flow type pump comprising stages which accomodate rotating impellers and stationary bowl possessing guide vanes. It may be oil or water lubricated. The principal advantages of the pump are: (i) it can be driven with an electric motor or an engine, (ii) it is more sturdy than a submersible pump, and (iii) it provides less wear and tear. However, the initial cost of the pump is higher than that of a submersible pump of identical capacity and head. Its installation is more difficult.

11.1.1 Principles of Operation

The impeller of the turbine pump operates on a modified radial flow centrifugal principle. Water enters the impeller near its centre and is whirled out towards the periphery at a high velocity by virtue of centrifugal force. The bowl has stationary guide vanes surrounding the impeller. As the water leaves the impeller, the gradually enlarging vanes direct it upwards, through velocity head partly converted into pressure.

As with all centrifugal pumps, the pressure head developed in a turbine pump bowl assembly depends on the diameter of the impeller and the speed at which it is rotated. In a deep well turbine pump, the diameter of the bowl and that of the impeller inside it are restricted by the relatively small diameter of the tube well. Hence, the pressure head developed by a single impeller, known as a single-stage pump, is not large. The maximum practical head is about 10 to 20 metres per stage. Additional head is obtained by adding more stages. Since each stage is identical, the total head is calculated by multiplying the head for a particular discharge by the number of stages, to get the combined value. The combined input energy of the pump is the sum of input energies for each stage. The combined efficiency of a multi-stage pump is given by the relationship,

$$\eta = \frac{Q\,(H_{s1} + H_{s2})}{102\,(P_{s1} + P_{s2})} \tag{11.1}$$

where, Q = discharge capacity of pump, 1/s

H_s = head of each stage, m

P_s = brake horse power for each stage, kW

The pumping action in a multi-stage deep well turbine pump is similar to that of an ordinary multi-stage centrifugal pump. Water under pressure, discharged from a lower stage, is directed vertically upward into the centre of the next higher impeller. The next stage adds a similar amount of pressure head to the water and, in turn, delivers it to the impeller above it, and so on. The same amount of water passes from stage to state. From each stage it receives an additional amount of head, until it finally leaves the last stage, with a total head equal to the sum of the pressures it has received from the individual stages, and passes up the discharge column.

Like volute pumps, turbine pumps are capable to producing a high discharge. The design of the impeller and bowl affect the capacity of the pump. The capacity is determined by the area through which the flow occurs and the velocity of flow. The velocity is determined by the peripheral speed of the impeller so that the quantity is determined by the width of the impeller. Of two impellers of the same diameter, the one having a greater width will have a greater capacity.

11.1.2 Construction

Vertical turbine pumps may be water-lubricated or oil-lubricated, with enclosed or semi-open type impellers (Fig. 11.1). It comprises mainly three parts: the pump element, discharge column and discharge head.

Pump Element

The pump element (Fig. 11.2) is made up of one or more bowls or stages. Each bowl assembly consists of an impeller and a diffuser and a bearing. The bowl assembly remains beneath the water surface. It has a screen or strainer fixed to its bottom to keep coarse sand and gravel from entering the pump. Impellers used are either enclosed or semi-open. Enclosed impellers permit higher efficiencies, but require a seal to prevent by-passing of water from the high-pressure to the low-pressure side. Another advantage of the enclosed impeller is its smaller down-thrust. In large pumps, the axial thrust must be reduced to avoid excessive shaft stretch and to keep the size of the shaft and thrust bearings within reasonable limits. Wear occurs at the suction opening on the 'eye' of the impeller. Semi-open impellers have the outer edges of vanes open. No seal is required, but there is wear on the edges of impeller vanes. A semi-open impeller can handle suspended solids with a minimum of clogging, a feature which is necessary in smaller pumps with their smaller water passages. In general, semi-open impellers are usually recommended for turbine pumps of size 20 cm and lower in diameter, and enclosed impellers for pumps larger than this. Impellers are made of gun metal, bronze, cast iron coated with porcelain enamel or teflon. Bronze will not rust or pit as does cast iron. However, when cast iron is protected by porcelain enamel, it has longer life.

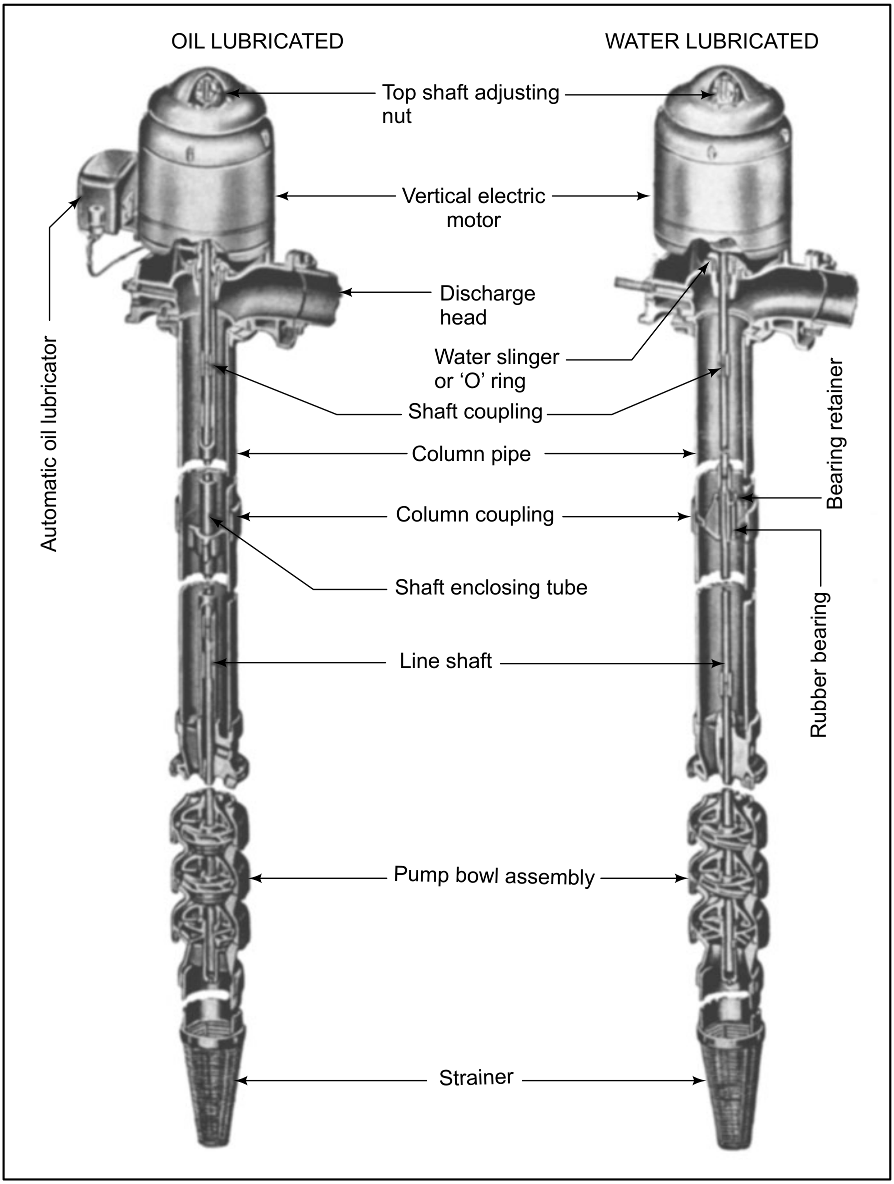


Fig. 11.1 Sectional views of oil-lubricated and water-lubricated vertical turbine pumps showing main parts and their assembly
Adapted from: Johnston Pumps (India), Ltd. Calcutta (Anon., 1968a)

The pumping element is designed as a matched assembly, the design of the individual impeller designating the design of the companion bowl. Bowls are usually made of vitreous porcelain enamel close-grained and cast iron lined. Impeller shafts are usually made of stainless steel. Bronze is standard for bearings.

Discharge Column of Vertical Turbine Pumps

The discharge column contains the delivery pipe and the shafting with its couplings and bearings. The construction of the column assembly differs with the method of lubrication of the pump, i.e. oil-lubricated or water-lubricated. Figure 11.3 illustrates the constructional features of the column assemblies of the two types. Column pipes and shafts are usually supplied in 3-metre lengths. Column pipes are made of steel and joined by threaded sleeve-type couplings. The drive shaft is located at the centre of the discharge pipe. It is made of cold-finished-carbon steel, of ample size to operate the pump without distortion or vibration. When oil lubricated, the drive shaft is enclosed in a cover pipe which guides the oil to the proper parts. Bronze bearings are provided every 1.5 metres. The bearing also serve as couplings for the cover pipe. The shaft and cover-pipe assembly are supported and aligned by reinforced rubber spiders, spaced in the column about every 15 metres. The oil-lubricated column has the advantage that the shafting is protected from any abrasive or corrosive elements that may enter the pump. This type of construction provides a more positive system of shaft and tube alignment.

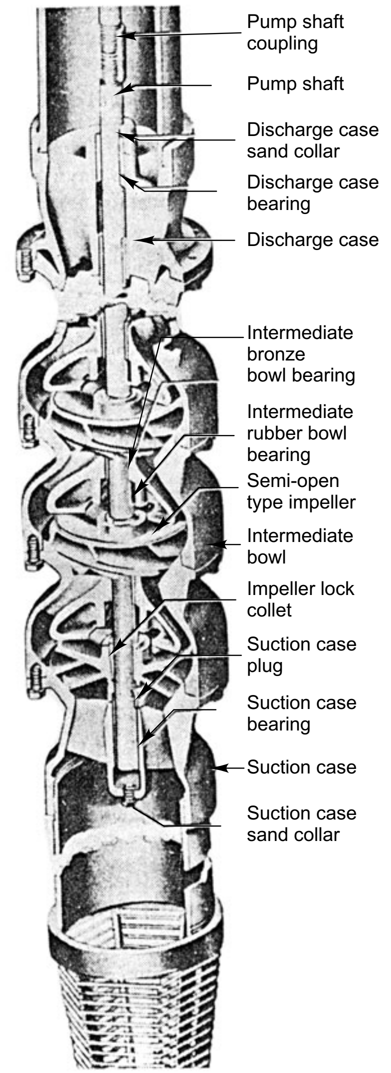


Fig. 11.2 Pump bowl assembly in water-lubricated pump with semi-open impellers

In water-lubricated pumps, the bearings, lubricated by the water being pumped, are of natural or synthetic rubber, set in bronze retainers. A renewable stainless steel sleeve, which eliminates shaft wear, shrouds the line shafts at the points of bearings contact. A cover pipe is unnecessary. The shaft is held in line by rubber bearings placed at three metre intervals. Rubber bearings are safely lubricated only when wet. Water-lubricated columns are provided with a pre-lubrication system, consisting of a water storage tank placed near the discharge head. Water is made to run through an inlet provided in the discharge head, down the discharge column, before starting the pump each time. This wets the rubber bearings and prevents their getting overheated and damaged.

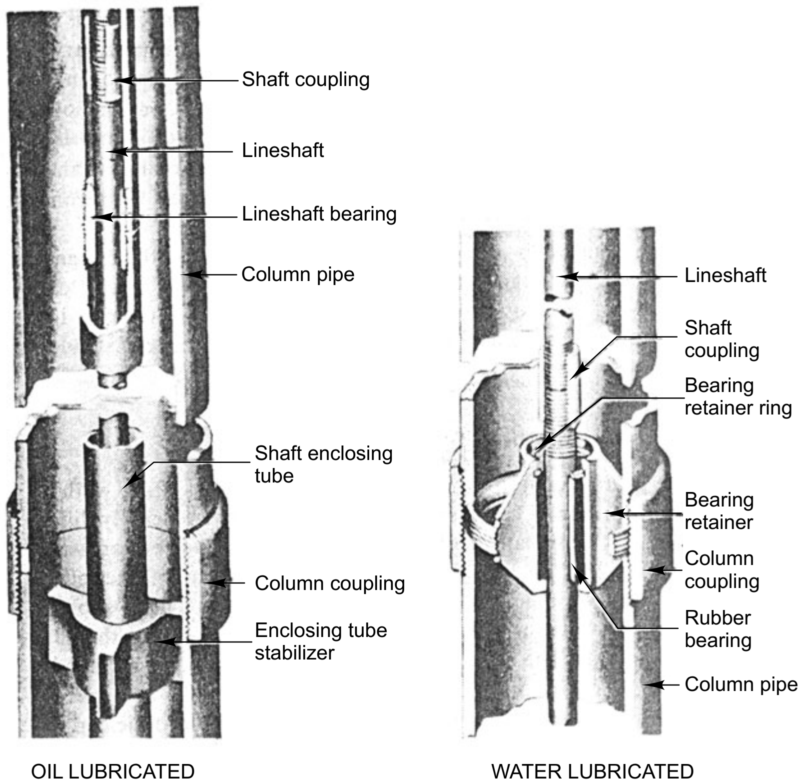


Fig. 11.3 Cut-away views showing the details of the column assembly of oil-lubricated and water-lubricated vertical turbine pumps
Courtesy: Johnston Pumps (India) Ltd., Kolkata (Anon., 1968a)

Discharge Head of Vertical Turbine Pump

The pump column assembly is fixed to the discharge head (Fig. 11.4), which is located at the ground surface. The base of the discharge head is bolted to the pump foundations. Electric motors, right-angle gear drives, flat or V-belt pulleys, and suitable combinations of these drives may be used on the same discharge head. Made of cast iron, the discharge head is simple in construction and provided with large waterways. The discharge elbow is equipped with flange to which the discharge pipe may be fixed. Provision is made for the pre-lubrication of water-lubricated shaft bearings, by means of a threaded port in the head.

11.1.3 Characteristics of Vertical Turbine Pumps

Efficiency curves of turbine pumps are similar to those of volute centrifugal pumps, if they are operated at the design speed. The operating characteristics depend upon the design of the impeller and the bowl, and the speed of rotation. Turbine pumps cannot operate at a high efficiency, over as wide a

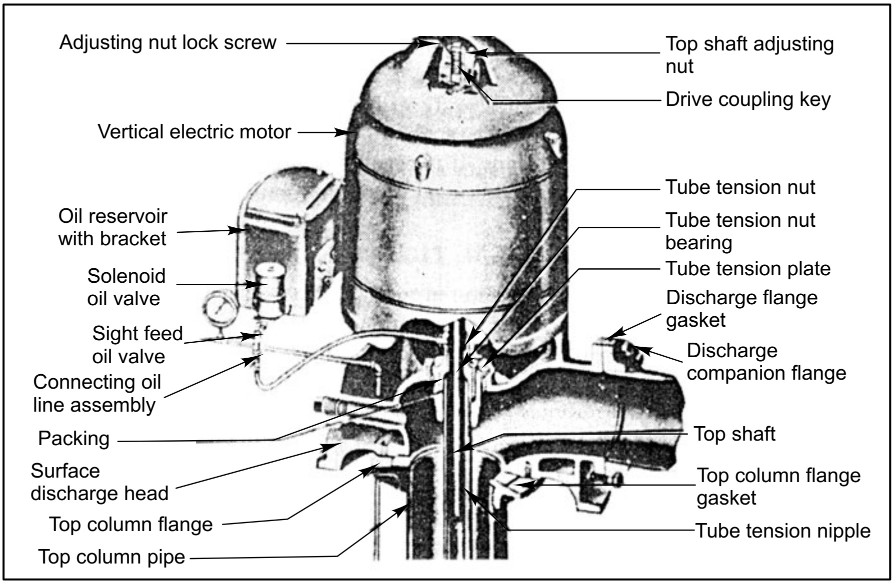


Fig. 11.4 Partially exposed view of the discharge head assembly and vertical electric motor of an oil-lubricated vertical turbine pump
Courtesy: Johnston Pumps (India) Ltd., Kolkata (Anon., 1968a)

range of speed, as can volute pumps. This is because a high efficiency is possible only if the vanes in the bowl are in line with the flow of water as it leaves the tip of the impeller. If the speed of the impeller is changed, the direction of flow of water leaving it is also changed. This will cause turbulence against the vane and will result in reduced efficiency.

The impeller is designed to meet the conditions of speed, capacity and head, at the point of highest efficiency. An impeller having narrow blades, with a large ratio between the diameter of the eye of the impeller and the impeller diameter, would be of lower capacity but higher head than an impeller having larger blades with a smaller ratio of eye diameter to impeller diameter. The latter would be a high-capacity pump with a lower head.

The performance characteristics of a turbine pump can be controlled by the pump designer by varying the design of impeller and bowl. These operating characteristics, when ascertained by tests, can be plotted on graphs, which give a clear picture of the performance of a particular impeller design. The characteristics curves form the basis for selecting the type of impeller to suit a particular requirement.

Operating characteristics of a turbine pump may be determined by an inspection of the characteristics curves furnished by the manufacturer. The characteristics curves represent the action of a single stage of the pump, under various operating conditions. If the required head is more than can be furnished by a single stage, additional stages may be added.

11.1.4 Selection of Vertical Turbine Pumps

The vertical turbine pump manufactured today is fairly well standardised, both as to materials used and general assemblage. The main difference between the various makes of turbine pumps is in the design of the bowl and impeller and in the method of lubrication. Both oil-lubricated and water-lubricated pumps have been operating successfully. When the pumped water contains fine sand particles, oil-lubricated pumps are preferred. Water for drinking purpose should be free of oil, and since oil-lubricated pumps lose some oil into the water, it is desirable that water-lubricated pumps be used. In cases where the pump has to stand idle frequently for considerable time, it is desirable to have an oil-lubricated pump, as the rubber bearings of water-lubricated pumps may get out of shape and damaged.

Each reputed pump manufacturer has developed a series of pump bowls having definite performance characteristics. These bowls may be used singly or in a series, to meet any combination of head and discharge, with a reasonably high level of efficiency. One of the main points in selecting the product of a particular manufacturer is the efficiency guaranteed over the range of pumping heads and discharge specified.

Data for Selecting a Turbine Pump

Selection of proper pump bowls and a matching column assembly will depend on well data. The pump should match the characteristics of the well. The well should be tested before a pump is purchased for permanent installation. The following information are usually required to determine, the type and size of pump needed to fit the characteristics of a well:

— Depth of well, m
— Inside diameter of well casing, m
— Dimensions of well pit, if any, m
— Depth to static water level, m
— Depth to static water level at the desired capacity, m
— Capacity of pump, l/s
— Drawdown-discharge curve of well
— Data on seasonal fluctuation in water table
— Preference for oil or water-lubricated pump design
— Source of power: Electricity: Voltage, phase and cycle,
Stationary engine: Diesel/petrol; Tractor:
Belt-pulley size and speed

Other information, like the quality of water to be pumped and the condition and alignment of the well bore are also furnished, if necessary.

Most companies offering vertical turbine pumps have built up their own data from which the parts of the pump are selected and matched to meet a specific condition. Both hydraulic and mechanical troubles can result from improper pump selection.

Details regarding the selection of pumps, based on their characteristics described in Ch. 9, apply equally to turbine pumps also.

11.1.5 Pump Drives

Power is supplied to the turbine pump at the surface. One of the main advantages of the turbine pump is its adaptability to different types of drives and power sources. The drive may be direct drive, right-angle gear drive, or belt drive (Fig. 11.5). The efficiency of a drive mechanism may greatly affect the operating costs of a pumping set.

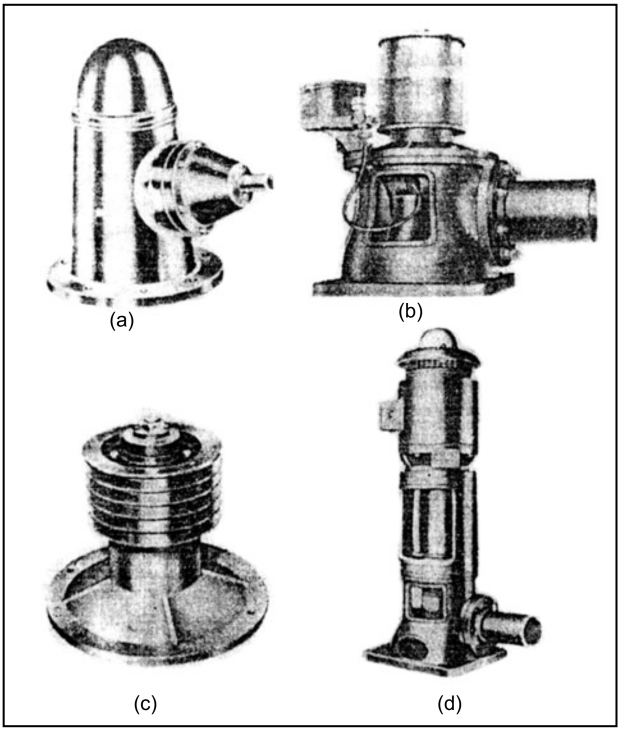


Fig. 11.5 Different types of drive heads for vertical turbine pumps: (a) Gear head for engine/belt drive, (b) Pulley head for flat-belt drive, (c) V-belt drive-head with grooved pulley, (d) Combination head for electric motor drive and engine drive.
Courtesy: Jyoti Ltd., Vadodara (Anon., 1971a)

Direct Drive

Direct drive is the most efficient as there is no loss of power, as with other drives. It is limited to conditions where the speed of the driver is the same as that of the pump. At places where electricity is available, a vertical electric motor directly coupled to the pump is the cheapest and most efficient type of drive. For most pumping conditions, the standard vertical hollow-shaft motor with a drip-proof shield is sufficient. Turbine pumps have a low starting torque requirement and are usually equipped with normal-torque squirrel-cage induction motors. Turbine pump horse power requirements increase as the cube of the speed, enabling the motor to start and easily pick up the gradually increasing load, as the speed increases. Vertical hollow-shaft motors employ a thrust bearing and a non-reverse or self-release coupling.

Belt Drive

Belt drives may be either flat belt or V-belt. The flat belt drive is the least efficient of all the types of drives. Its efficiency varies from 80 to 90 per cent, depending on slippage, type of pulley and belt, pulley size, number of idler pulleys used, and the type of twist used. Slippage is the main cause of loss of efficiency. The pump head and flat pulley drive of a water-lubricated vertical turbine pump is shown in Fig. 11.6.

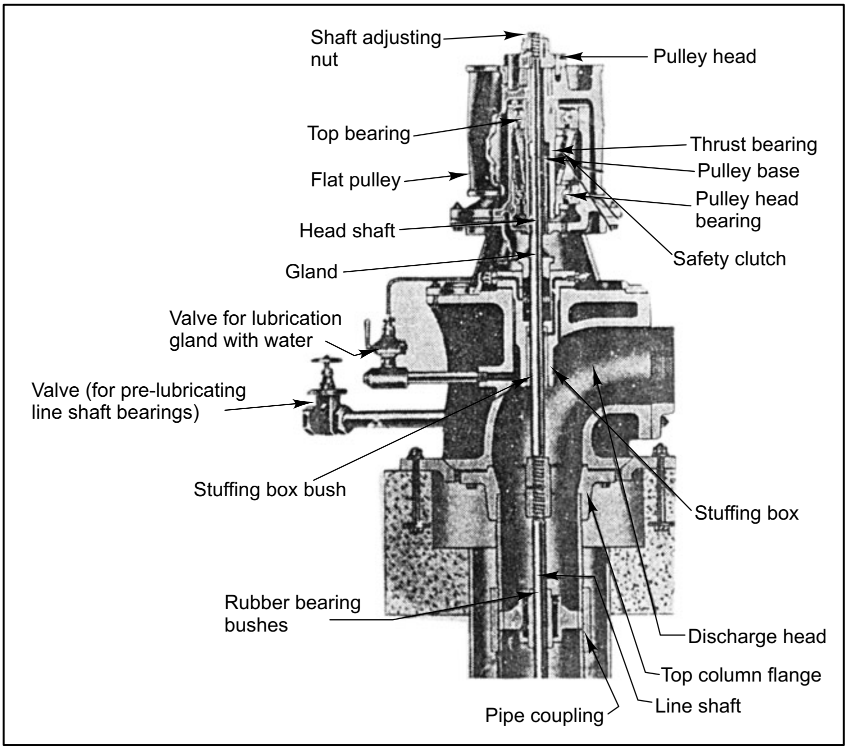


Fig. 11.6 Pump head and flat belt pulley drive of water-lubricated vertical turbine pump
Courtesy: Jyoti Ltd., Vadodara (Anon., 1971a)

To drive a vertical turbine pump from the horizontal shaft of an engine, with a belt, a quarter-twist drive is required. Flat belt drives are generally employed with tractor belt pulleys, and sometimes with stationary engines and motors.

The V-belt drive is more dependable than the flat belt drive, and has a higher efficiency. Its efficiency varies from 90 to 95 per cent under proper operating conditions. However, it requires closer spacing between the pulley centres.

Figure 11.7 shows the desired arrangement of the flat-belt drive for a vertical turbine pump. Specifications for flat belts quarter-twist drives are given in Table 11.1.

TABLE 11.1 Flat Belt Specifications of Quarter-Twist Drive of Vertical Turbine Pumps

HP	Leather belts		Rubber belts		Minimum centre to centre distance '*A*'	
	Width cm	Ply	Width cm	Ply	Motor drive m	Engine drive m
10	10.0	1	12.5	3	3	4.5
15	12.5	2	12.5	4	3.6	5.5
20	15.0	2	15.0	4	4.2	6.5
30	20.0	2	20.0	5	4.8	7.5
50	25.0	2	25.0	5	5.4	9.0

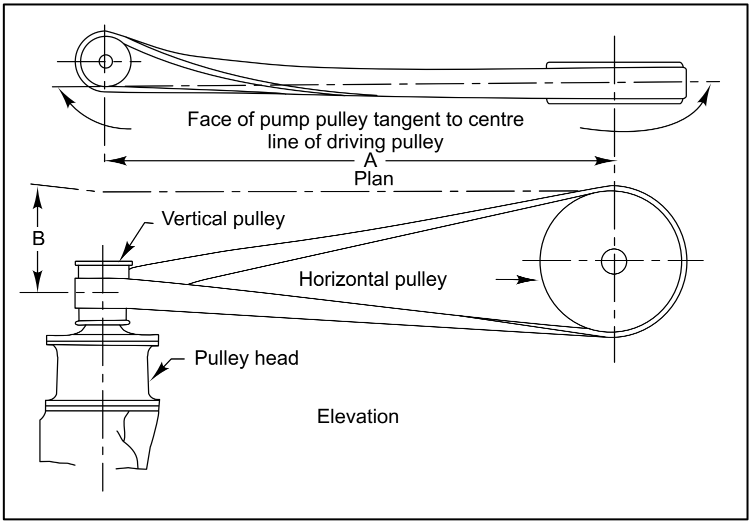


Fig. 11.7 Quarter-twist flat belt drive for turbine pumps showing the basic requirements in installation

To allow for belt sag, the centre of the face of the driving pulley is raised 6.25 cm for each 1 m distance between the centres of the driving and driven pulleys. For example, if the centre-to-centre distance is 3.6 m, the dimension B will be 22.5 cm. The minimum recommended pulley diameters for single and double-ply leather belts are 12.5 cm and 17.5 cm, respectively. For rubber belts of 3, 4 and 5 ply ratings, the minimum pulley diameters recommended are 15 cm, 17.5 cm and 25 cm, respectively.

The arrangement of a V-belt drive, as shown in Fig. 11.8, may be used with speed ratios from 1:1 to about $2\frac{1}{2}$: 1. On these types of drives, a belt length should be chosen which will give a minimum centre-to-centre distance of 5.5 ($D + W$), where D is the diameter of the large sheave and W is the width of the band of belts. Looking down on the drive, a line from the centre of the vertical shaft should pass through the centre of the sheave on the horizontal shaft, and the horizontal shaft should be at right angles to this line. Looking to the side of the drive, the centre of the horizontal shaft should be raised a distance Y above a level line through the centre of the face of the sheave on the vertical shaft. The value of Y is given in Table 11.2. A belt-drive head with grooved pulley for V-belt is shown in Fig. 11.5 (c).

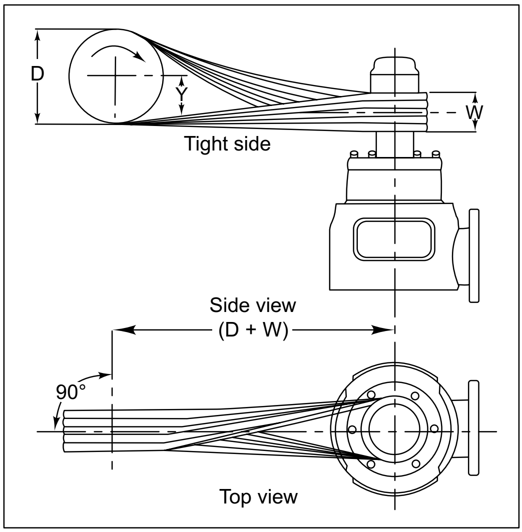


Fig. 11.8 Views of quarter-twist V-belt drive for vertical turbine pump
Courtesy: Toowoomba Foundry Pvt. Ltd., Australia (Anon., 1968b)

TABLE 11.2 Distance between the Centre of the Drive Pulley and the Face of the Driven Pulley in V-Belt Drives for Vertical Turbine Pumps

Centre distance m	Dimension *Y* cm	Centre distance m	Dimension *Y* cm
1.5	6.25	4.0	16.25
2.0	6.90	4.5	19.35
2.5	7.50	5.0	22.50
3.0	10.00	5.5	26.25
3.5	13.15	6.0	30.00

The V-belt cross-sections and number of belts required to transmit a given horse power are selected from manufacturers' catalogues. The direction of rotation of the driving pulley must be such that the tight side of the drive will be at the bottom.

Right-Angle Gear Drive

The right-angle gear drive provides the most dependable and efficient method of transmitting power from horizontal prime movers to vertical pump shaft. An exposed view of the right-angle gear drive is shown in Fig. 11.9. The efficiency of the gear drive is about 95 per cent or more. These units are made to match any standard pump and are made with a variety of gear ratios to permit the pump and engine to operate at their desired speeds. Gear drives fill an important need in places where electric power is not economically available. The drive is much more efficient than belt drives and is not affected by climatic conditions as is the case with belts.

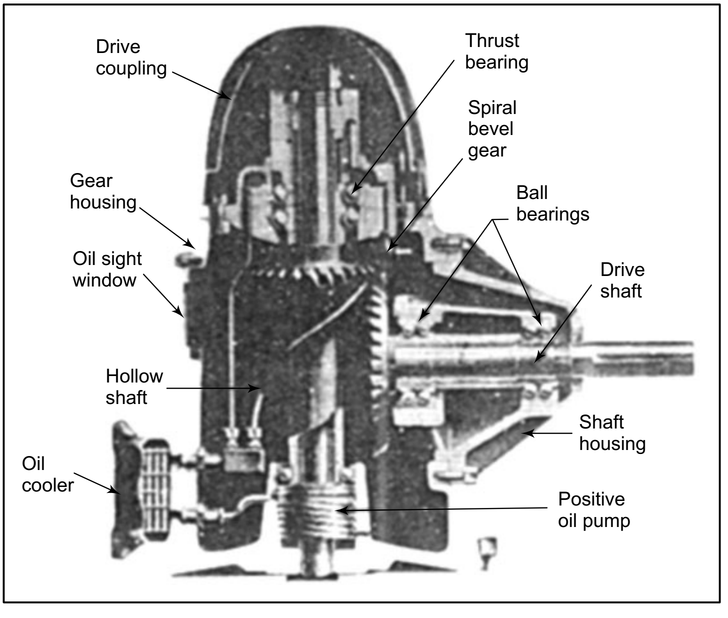


Fig. 11.9 Exposed view of a right-angle gear drive for vertical turbine pump
Courtesy: Johnson Gear & Manufacturing Co. Ltd., Berkely, California, USA.

The most commonly used installation is a gear drive directly connected by a flexible shaft to a stationary engine (Fig. 11.10). Sometimes, a vertical turbine pump with right-angle gear drive is also operated by a tractor, using pulleys and flat belt. Combination drives (Fig. 11.5d) permitting the use of electric motors or engines, as and when each one is required, are also available. They are more commonly used in water-supply systems and other essential services, as a protection against the hazards of electric power failure.

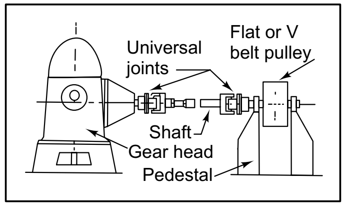


Fig. 11.10 Shaft drive using universal joints to link right-angle gear head unit to engine shaft or belt pulley *Courtesy:* Johnson Gear Mg. Co. Ltd., Berkely, California, U.S.A.

Although the gear drive has maximum efficiency when directly connected to the pump, there are situations when a belt connection is desirable. The use of a gear drive eliminates the need for a quarter-twist belt in such applications. Usually, the diameter and offset of pulleys that may be used directly on the gear-drive shaft are restricted to prevent over-loading of the drive shaft bearing.

The selection of a gear drive is based on the horse power required to operate the pump and the thrust conditions of the pump. The total pump thrust is the combined weight of the rotating parts of the entire pump plus the hydraulic thrust. The thrust load varies with the size and number of stages, shaft size and total head.

11.1.6 Installation of Vertical Turbine Pumps

The procedure of installation of a vertical turbine pump includes various steps like preparatory work, actual installation and testing. The various steps involved are discussed below.

Preparatory Work

The initial preparation will include checking the condition of the tube well and pump house, availability of tools, etc. This will prevent considerable delay in installation and ensure trouble-free operation after installation.

Tube Well

The basic information on the tube well, as regards the diameter of the housing pipe, well log and results of well development, are collected. The diameter of housing casing would determine the suitability of lowering the given pump. In case the well has not been developed earlier, it should be completed before installing the pump. The water should be free of sand. Information on the static water level and the possible drawdown are collected to determine the length of the column pipe.

The results of the verticality test of the tube well should be reviewed. To ensure satisfactory operation, the pump should hang free and in plumb in the well. A pump may be installed in a non-vertical well, provided the non-verticality is uniform, in one direction and within the allowable limits. If the tube well has kinks or dog legs, a turbine pump should not be installed in it. In case the well is out of plumb, the diameter of the housing/casing should be such that there is enough annular clearance, so that pump can still be hung free and vertical. Should the pump be installed in an open well, no verticality test is required.

Pump House and Ancillary Equipment

Before installing the pump, it should be ensured that the pump house has been constructed as per the standard design, to provide easy operation and maintenance of the pump. The pump foundations should also conform to a standard design. This becomes more important in case of gear-driven and belt-driven pumps. In this case, the foundation for the engine or the horizontal motor are properly aligned and centered. The size of the pump house depends on the type of drive used. The design of a typical pump house for installing vertical turbine pumps is given in Fig. 11.11.

If the pump house has been constructed, and its roof is strong enough, a tripod may be erected on top of the roof, centered around the manhole opening. The other possibility is to use an I-beam, mounted on two pedestals built on either side of the manhole. It is centrally located over the manhole. The I-Beam should be strong enough to handle about twice the weight of the pump unit.

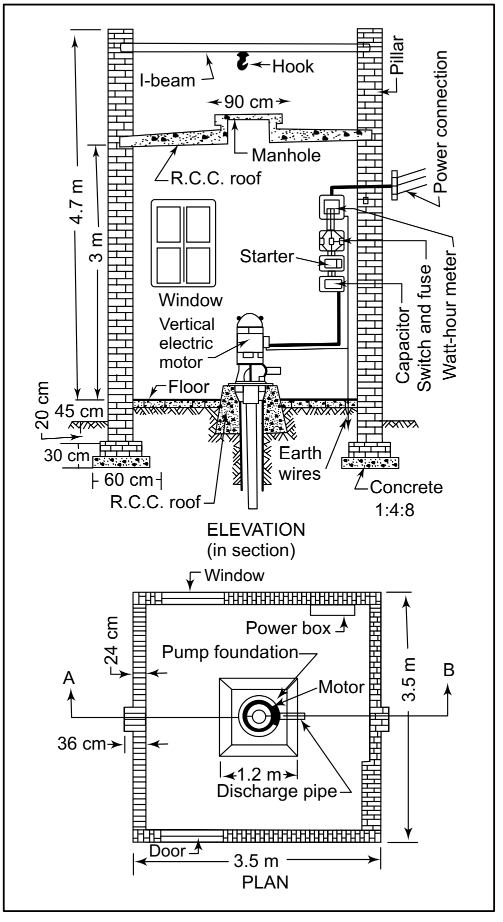


Fig. 11.11 Views of a pump house and electrical connections for installing turbine-type pumps

Arrangement of Pump Assembly

All the components of the pump should be arranged near the tube well (Fig. 11.12). The bowl and column assembly are arranged so that the end facing up should be towards the well. The top 1.5 m section of the column assembly is distinguished from the bottom 1.5 m by the absence of the coupling. The top column pipe section does not have the oil tube and shaft, as the tube tension nipple and head shaft serve their purpose. Hence, the oil tube and shaft assembly of turbine pumps are 1.5 m less than the column pipe. The tools should be kept neatly arranged, preferably on a tool rack, and placed on one side where they are handy. After using a tool, it should be replaced in its original position. This will prevent hunting around when the tool is required again and also prevent the tools getting dirty.

Installation of Oil-Lubricated Vertical Turbine Pumps

The step-by-step procedure for the installation of an oil-lubricated vertical turbine pump is as follows:

1. Fix the conical strainer to the bowl assembly, if required (The use of strainer is optional when the pump is to be installed in a tube well. However, its use becomes essential when the pump is to be

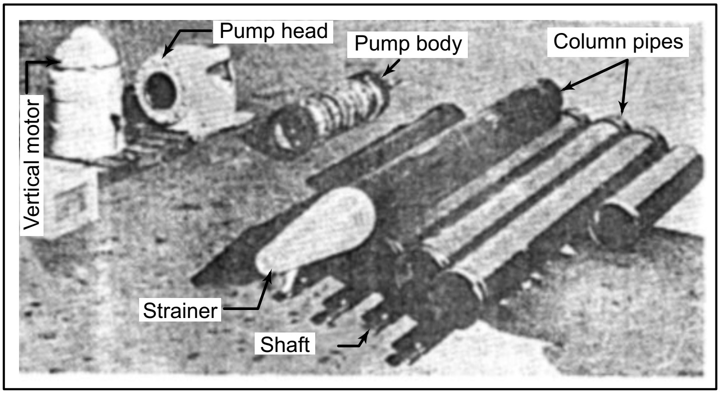
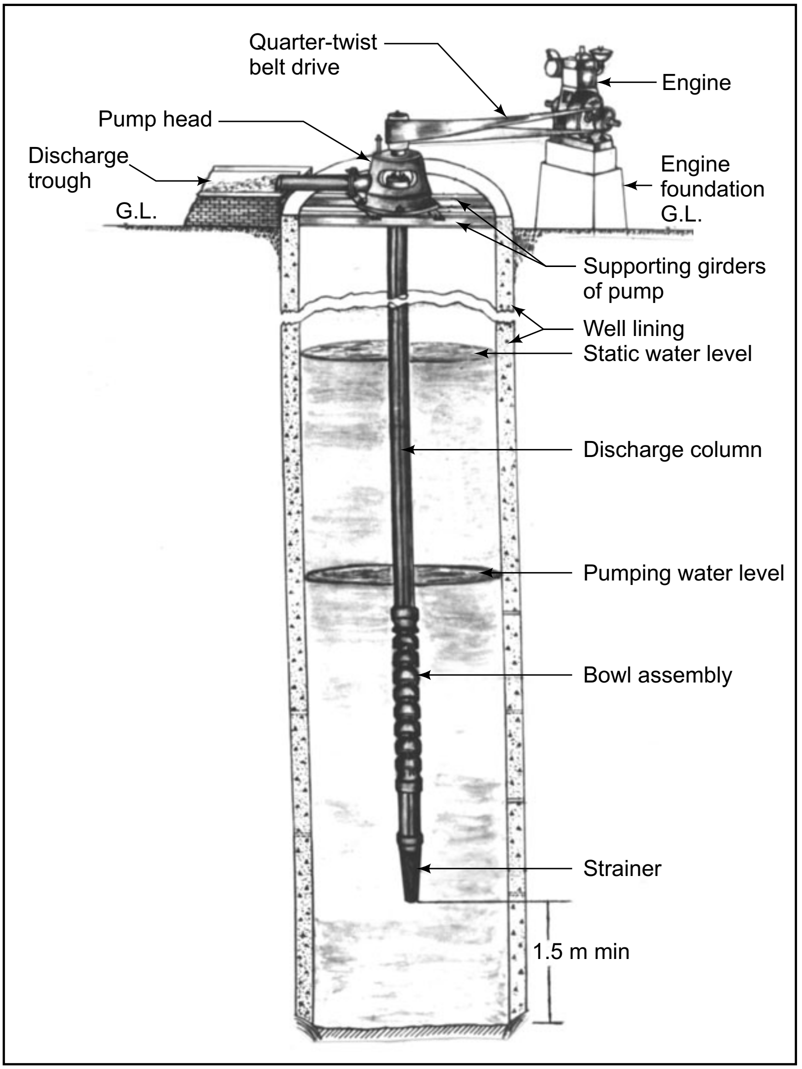


Fig. 11.12 Vertical turbine pump parts laid for installation. Left to right are the vertical electric motor, pump head, column assembly, suction pipe, strainer fixed to bottom pipe of suction line, column pipes, shaft enclosing pipe and line shaft *Courtesy:* Johnston Pumps (India) Ltd., Kolkata (1968a)

installed in an open well (Fig. 11.13), to prevent the entry of debris and organic matter into the bowl assembly). If the suction pipe is to be used, lower the suction pipe with conical strainer into the bore till the pipe clamp fixed on the pipe rests on the beam placed across the bore.

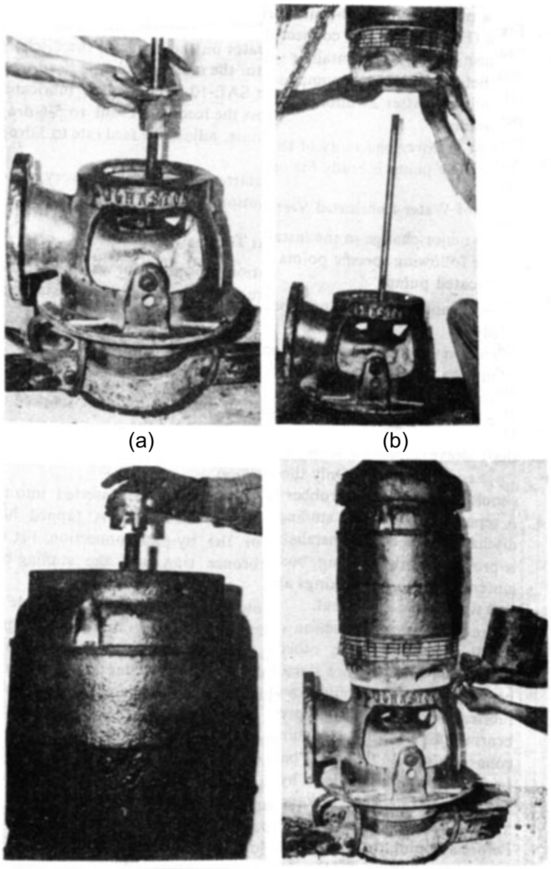
2. Fix another set of clamps to the discharge case of the bowl assembly and lift the bowl assembly. Never handle the bowl assembly by the protruding part of the impeller shaft.
3. Lower the bowl assembly and bolt the flange of the suction case to the flange of the suction pipe. Put rubber packing between the faces of the flange. Lower the complete unit till the clamp rests on the beam.
4. If the conical strainer is to be used directly with the bowl assembly, first fix the strainer to the suction case of the bowl assembly shaft with a spanner till it touches the impeller and the clamps fixed on the discharge case rest on the beams. In case the strainer is not used, the bowl assembly is directly lowered into the well with the help of a chain pulley block.
5. Remove the line shaft for first column assembly, clean the threads with kerosene, apply light coat of grease and screw it to the bowl assembly shaft nut. Tighten the line and lower the bowl shaft. Ensure that the coupling length is equally divided between the impeller shaft and the line shaft.
6. Apply a coat of thread compound on the projecting half of the line shaft bearing on the bowl assembly. Take a shaft enclosing tube, clean its ends and screw it by means of a pipe spanner.
7. Take the first column pipe and lower it on the bowl assembly. Apply light coat of thread compound, screw the column pipe to column pipe adapter of the bowl assembly by means of chain wrenches (In case of flanged column pipe, apply a coat of grease on matching flanges and tighten the nuts equally opposite, uniformly).
8. Remove the clamp fixed on the discharge case of the bowl assembly and lower the pump inside the well till the clamp fixed on the first column pipe rests on the beam/floor.
9. Fix a line shaft bearing to each of the shafts enclosing tubes at their mid-points. Pour few drops of SAE-40 mobile oil or equivalent lubricating oil into the gap provided at the top of the line shaft bearing.



11.13 Installation of engine-driven deep well turbine pump in an open well

10. Push the rubber spider into the casing pipe. Fix it by slow tapping with a hammer. Keep a wooden block over the spider to avoid direct blows of hammer on the rubber spider. At every 3 m column, one spider is to be inserted.
11. Take the column pipe coupling, clean it and apply a light coat of thread compound on the threads. Screw the column pipe coupling on to the column pipe upto half its length.
12. Continue assembling of line shafts, shaft tubes, bearings, spiders and column pipes till the required length of column is obtained. After the installation of every column, check the relative distance of the top of the face of the column pipe, shaft tubes and shafts. The relative distance should be maintained throughout the installation.

13. The top end of the top column pipe may be flanged or threaded. In case of threaded type, screw a cast iron bottom flange on the top column pipe.
14. Pour about half a litre of SAE-10 or equivalent oil through the shaft tubes. Screw up the line shaft bearing to shaft tube.
15. Connect the head shaft (keeping the key-way end up) to the line shaft by the line shaft coupling.
16. Screw up the tube nipple on the line shaft bearing.
17. Remove rubber packing and gland nut from discharge head. Clean the discharge head and lower it on the bottom flange (Fig. 11.14a), taking care to see that it does not knock against the head shaft. The tube tension nipple will adjust its correct portion.
18. Insert rubber packing between the bottom flange and the discharge head. Fix the discharge head and tighten the nuts (Fig. 11.14a).
19. Insert rubber packing around the tube tension nipple. Screw up the gland nut which will tighten the tube tension nipple and simultaneously press the rubber packing. Lock the gland nut by inserting a bolt through the slot of the gland nut.
20. Level the discharge head by means of a sensitive hand level and adjust the level by putting metallic shims below the discharge head base.
21. Connect the delivery pipe and check the level of the discharge head again. For levelling, put props below the delivery pipeline. Grout the delivery pipeline after the proper level is obtained. Check the level of the discharge head again and bolt the pump base to the foundation.
22. Installation of electric motor: Remove the motor top shelter and check whether the motor is rotating freely. Join the power connection to the motor terminals and ensure that the direction of rotation is anti-clockwise, looking from the top. If not, interchange any two terminals of the motor.
23. Raise the vertical motor up to head shaft height and slide it over the projected head shaft (Fig. 11.14b). Take care to see that the head shaft enters the hollow shaft of the motor easily, without knocking it. Bolt the motor over the discharge head top flange.
24. On the head shaft, slide the top half coupling with the non-reversible ratchet pins in position. Fix the jib key in the head shaft. Rotate the coupling of the motor so that its holes match the pins of the top coupling.
25. Tighten the impeller adjusting nut on the head shaft (Fig. 11.14c) till it is flush with the top surface of the coupling block. Count the turns of the impeller adjusting nut required for the impellers to touch the inner top face of the bowl. Unscrew the impeller adjusting nut to half the number of turns counted for total lift of the impellers. Tighten the set screw to lock the impeller adjusting nut for this particular position.
26. Fix a magnetic/hydraulic oil lubricator on the flange of the discharge head (Fig. 11.14d) and connect it to the motor/discharge head water connection. Fill the container with SAE-10 or equivalent lubricating oil. Before starting the pump, adjust the feed rate of oil to 5-6 drops per minute. After 24 hours of running, adjust the feed rate to 3 drops per minute.
27. Adjust the overload relay of the starter. Open the delivery sluice valve. The pump is ready for operation.



(a) (b) (c) (d)

Fig. 11.14 Installation of head assembly of oil-lubricated vertical turbine pump: (a) Inserting gland bush after installing the pump head on the flange coupled to the top casing pipe, (b) Lowering of vertical electric motor to the head shaft, (c) Locating the impeller adjusting nut on the head shaft, (d) Fixing the oil lubricator assembly to the discharge head.

Installation of Water-Lubricated Vertical Turbine Pumps

There is no major change in the installation procedure for water-lubricated pumps. The following specific points are kept in mind while installing a water-lubricated pump.

1. There is no shaft enclosing tube, so all references made on it do not apply.
2. Each 3 m column has a cast iron spider with rubber bearing. This should be installed before the column pipe coupling is screwed on to the column pipe.
3. The line shaft must have a stainless steel shaft sleeve. First, the line shaft sleeve should be screwed on to the line shaft, and then the shaft coupling fixed. (Only the surfaces of the stainless steel sleeves should be covered with rubber bearing).

4. A separately assembled stuffing box unit should be inserted into the discharge head before installation of the head shaft. A tapped hole is provided in the stuffing box for the by-pass connection. Fix the lantern ring, gland packings and bronze ring into the stuffing box and tighten the gland nut.
5. A pre-lubrication connection should be given to the tapped hole on the discharge head. The other end of the connection is for the pre-lubrication tank. Before starting the pump, pre-lubricate the rubber bearings for about 5 minutes with clear cold water from the pre-lubrication tank. Lack of pre-lubrication may damage the rubber bearings as well as the pump. The valve of the pre-lubricating connector should be closed before starting the pump.
6. Leakage through the gland by-pass should be regulated by a cock. There should be some leakage through the gland, otherwise there is a possibility of the head shaft jamming and the gland heating.
7. Before stopping the pump, the pre-lubricating tank should be filled by opening a valve of the pre-lubricating connector given to the discharge head.

Installation of Right-Angle Gear Head/Pulley Head Drive

If a right-angle gear head or pulley head is to be installed in place of the vertical motor, the following points are to observed:

1. The right-angle gear head is filled to the oil-level mark on the indicator window, with high-grade gear oil. The pulley head, if used, is filled with SAE 30 or equivalent oil till oil reservoir connected to the pulley head is filled fully.
2. The right-angle gear head/pulley head is lifted and lowered on the discharge head in such a way that the head shaft enters the hollow shaft of the drive smoothly. The bolts are fixed on the discharge head flange, which is made accurately for the respective drive. The nuts are tightened perfectly.
3. Lift adjustment of the impeller is done in the same manner as in the case of motor-driven pumps.

Telescopic Shaft with Flexible Coupling

Sometimes, the gear drive is directly connected to a diesel engine through a telescopic shaft with flexible coupling. The following are the specific steps involved in its installation:

1. Slip the standard flange supplied on to the gear drive shaft extension. Put in the key and lock the flange in position with the help of a set screw (provided).
2. Connect one end of the flexible shaft to the standard flange with the help of bolts, nuts and lock washers (supplied).
3. If the drive is mounted on slide rails, it may be moved forward or backward for precise adjustment. If, however, the drive is on a fixed foundation, the length of the flexible shaft can be adjusted by loosening a cap nut on the spline shaft to the desired length.
4. While installing the flexible shaft, it should be ensured that the driving and driven units are parallel and the lugs in line.

5. In case of horizontal motors, it is recommended that they be mounted on slide rails so that the necessary centre-to-centre distance may be adjusted in the field. It is recommended that diesel engines be mounted solidly on a fixed foundation. Any adjustment in distance is done by the slip joint provided in the flexible shaft.

For connecting the discharge pipe to the pump head of high capacity vertical turbine pumps, a flexible link pipe is often used to avoid damage to the head assembly (Fig. 11.15).

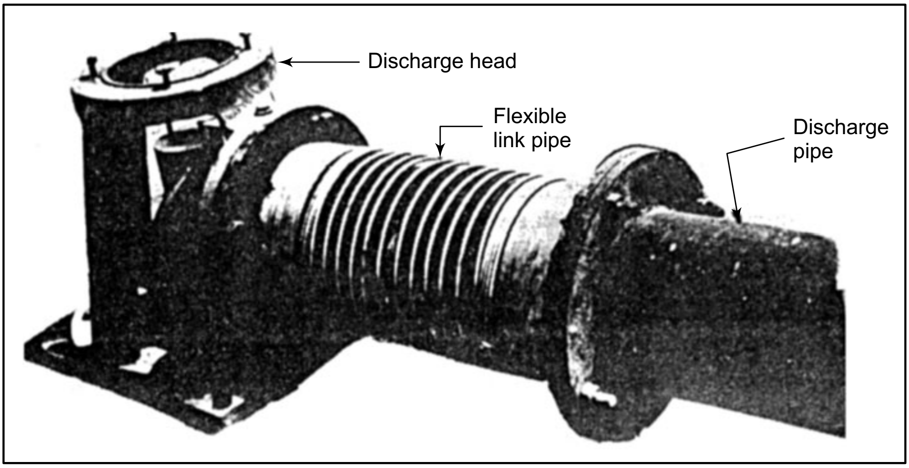


Fig. 11.15 Discharge head assembly of a vertical turbine pump using flexible link pipe at the head end of discharge pipe

11.1.7 Operation of Vertical Turbine Pumps

After completing the installation of the pump unit (Fig. 11.16), as per instructions, the pump is ready for operation. Before starting the pump, the following points should be checked:

Motor-Driven Pumps

1. Check the electrical connection to the motor. It should be as per the diagram given inside the motor terminal box.
2. Check the starter and other electrical instruments. They should be connected as per the instructions.
3. Keep the delivery valve fully open. When the column length of the pump is short, keep the delivery valve partially closed.
4. For oil-lubricated pumps, ensure that the lubricating system is working perfectly. Adjust the lubricator for 5-6 drops of oil per minute, before starting the pump. After about 24 hours of running, reduce the feed rate to 3 drops of oil per minute.
5. For water-lubricated pumps, operate the pre-lubricating system before starting the pump.
6. Check all connections from the discharge head to the pump.
7. Pressure gauge valve should be closed.

8. Start the pump, open the pressure gauge valve and check the power. Close the pre-lubricating system.
9. Ensure that the pump runs smooth without any vibration.

Right-Angle Gear Head Driven Pumps

1. Check oil level in the right-angle gear head.
2. Check the cooling connection to the right-angle gear head.
3. Check the cooling connection to the engine.
4. Check the tightness of the belt (in case of belt drive).
5. Ensure that there is no V-groove of V-pulley head without V-belt (in case of belt drive).
6. The other points are as per the procedure for motor-driven pumps.

Pulley Head Driven Pumps

1. Check the oil level in the pulley head.
2. Check the cooling connection to the engine.
3. Check tightness of belts.
4. All V-grooves of V-pulley head are provided with V-belts (in case of V-belt drive).

The other points are the same as those for motor-driven pumps.

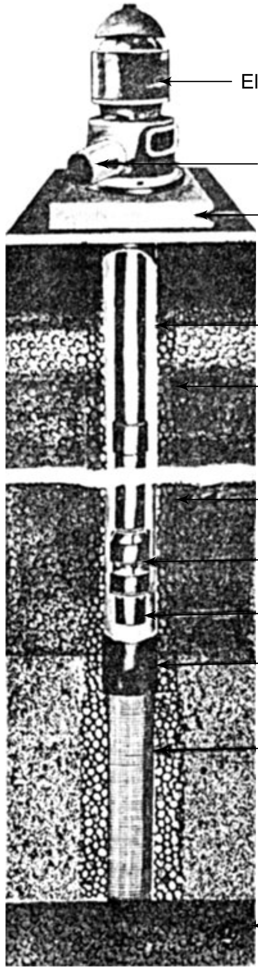


Fig. 11.16 Sketch illustrating the installation of a vertical turbine pump in a tube well

Stopping of the Pump

Before stopping the pump, the following action should be taken:

1. For water-lubricated pumps, fill the pre-lubricating tank fully.
2. Close the pressure gauge valve.
3. Stop the pump.
4. Close the manually operated oil lubricator (in case of oil-lubricated pump).
5. Switch off all electrical equipment.
6. Close the fuel connection to the engine.

11.1.8 Pump Troubles and Remedies

When properly installed and adequately maintained, the turbine pump can be expected to give trouble-free service for long periods. Manufacturers' instructions on lubrication and servicing of the pump and drive heads are to be adhered to.

Common troubles of vertical turbine pumps and their remedies are listed below:

Pump does not Start

1. Faulty electrical connections of motor.
2. Excessive bearing friction due to misalignment of pump, insufficient lubrication or improper grade of lubricating oil, or dry rubber bearing in case of water lubricated pump.
3. Impellers are locked, improper impeller adjustment.
4. Pump is sand-locked.
5. Shaft is disengaged or broken.
6. Discharge packing is excessively tight.
7. Low voltage.

The remedies, in general, are evident from the causes of the troubles. Raising or lowering impellers may release them. Backwashing with clear water may clean the bowls. When other methods fail, it may be necessary to pull out the pump and set right the defect.

Pump does not Deliver Water

1. Pump suction broken.
2. Pump speed too slow. Check pump speed and see whether motor is getting full voltage.
3. Water level lowered such that pump bowls are not submerged.
4. Impellers plugged. This will happen when the tube well is not fully developed and the pump discharges clay and sand at the start. Bowl assembly will have to be pulled out and flushed with a hose. It may also be necessary to open the bowl assembly to clean thoroughly.
5. Impellers jammed on account of foreign matter in the bowls. In case of open wells, there is a likelihood of small pieces of wood or rags getting through the strainer and clogging the impellers.
6. Strainer clogged.
7. Wrong direction of rotation.
8. Pumping head too high.
9. Mechanical failure like broken shaft or bowl assembly, loose impellers or leakage in column pipe joints.

Insufficient Water

1. Speed too low.
2. Water level lowered so that all bowls are not submerged.
3. Worn out pump bowl and impellers.
4. Impellers loose or damaged.

5. Column joint defective and leaking.
6. Impellers or strainer partially clogged.
7. Improper impeller adjustment. This is an important factor in case of semi-open impellers, where a quarter turn of the adjustment nut makes considerable difference in discharge.

Insufficient Pressure

1. Speed too slow.
2. Air in water.
3. Pump bowls not submerged.
4. Worn out bearings.
5. Impellers damaged.
6. Column joints leaking.
7. Wrong impeller adjustment.

Pump takes Excessive Power

1. Operating conditions differ from those for which the pump is designed.
2. Poor lubrication.
3. Impellers not correctly adjusted. They may be too high, resulting in binding of flow against top of bowls, or too low, resulting in rubbing of impellers against bowl seats. In deep settings, the adjustment must counter the expected shaft stretch when the pump is working under full load.
4. Pumping sand. Impellers partially clogged and rubbing against sand deposited on the bowl seats.
5. Too much oil in the oil tube or oil used is too heavy.
6. Pump out of alignment.
7. Shaft bent.
8. Worn out or tight bearings.
9. Dirty oil used in lubrication. Impurities may bind the shaft against the bearings.
10. Improper greasing or oiling of bearings in the pump drive.

Pump Vibrates

1. Speed too high.
2. Pump improperly aligned and levelled.
3. Crooked well.
4. Bent shaft.
5. Impellers rubbing against bowl seats on account of improper adjustment.
6. The pump may not be properly bolted to foundation.
7. Pump not resting on solid foundation.
8. Bearing in drive not properly lubricated.
9. Loose impellers.
10. Imbalance due to foreign material lodged between impeller or bowl passage, vibration of drives or excessive wear in rotating parts.
11. Poor suction conditions.
12. Pump breaking suction and pumping air.

Capacity Too Low

1. Head too high.
2. Speed too low.
3. Poor suction conditions caused by turbulence, eddying and vortexing at the pump suction, air leaks in the suction pipe.
4. Leakage due to loose threads or flanges, worn gaskets or packing.
5. Incorrect impeller adjustment.
6. Mechanical failures like worn impellers, wearing rings, or bearings; or impellers loose on shaft.

Water Enters Shaft Tubes or Oil Mixes with Water

1. Tube joints not tightened flush.
2. Line shaft bearings broken.
3. Discharge head gland not properly tightened.
4. Dents or cuts on the tube faces.
5. Shaft enclosing tube leaking or broken.

Components Wear Out Quickly

1. Bearings run dry or with insufficient lubrication.
2. Bearings misaligned.
3. Tube well crooked.
4. Shafts bent.
5. Sand in water.
6. Vibrations due to misalignment or improper levelling of discharge head.

Deterioration of Impellers

Turbine pump impellers may deteriorate due to galvanic action, erosion, or cavitation. Galvanic action leads to corrosion of two different metals in the presence of impure water. Since the impellers remain submerged in water, this action continues even when the pump is not in operation. It may be necessary to select the material of the impeller on the basis of the quality of ground water. Erosion of the impeller may occur if the water contains sand or other abrasives. When these conditions are known to exist, an erosion-resistant material should be selected for the impeller. Cavitation is eating away of the impeller vane due to high velocity water, when the pump is operated at high speeds. The pump should be operated at the design speed.

11.1.9 Maintenance of Vertical Turbine Pumps

For safe and efficient operation, vertical turbine pumps should be maintained properly. Common maintenance procedures are given below:

General Considerations

The pump should be installed in a dry, clean and well-ventilated place, free from rain, moisture, wind and sand. It should be cleaned daily. There should not be dust, grease or oil on the outer surface of the pump unit. The oil level in the pulley head should be checked daily. Uniform feeding of oil from the oil lubricator should be ensured. Periodical checking of the tightness of belts (in case of belt driven pumps) and the levelling of the discharge head is required, as there is a possibility of foundation settling.

Lubrication of Pump Unit

Lubrication of oil-lubricated pumps should be with clean, dust-free SAE-10 oil. The level of oil in the reservoir should be checked once every 48 hours. If necessary, add fresh oil. Check oil in the reservoir if no oil flows through the feeder, as indicated by the sight feed valve. The solenoid coil should be checked for loose connections or burn out. If the solenoid is in good condition, the sight feed valve should be opened and blown through to remove any dirt. It is reassembled carefully and connected back to the line. For manual lubricators, precaution should be taken to stop the oil-feed to the line shaft after the pump is stopped. This is done either with the help of a stopcock, which may be provided, or by screwing in the needle valve.

As regards water-lubricated pumps, these may be provided with foot valves to retain pre-lubrication water, or with a pre-lubrication tank and fittings. In case a pump is fitted with a foot valve, the column assembly is filled with water up to the discharge head. However, in case the pump has been idle for a long period, it should be checked for water in the column pipe. If not, fresh water should be added. This can be done by disconnecting the discharge pipe and using a hose pipe to fill the column pipe till it is filled with water.

In case of water-lubricated pumps with a pre-lubrication tank, the tank should be cleaned before filling water (the water should be clean). Before starting the pump, the water from the tank should be allowed to flow out into the pump, for one minute for every 3 m setting, and an additional one minute for extra safety. Once the pump is started, the water from the well will be pumped into the pre-lubrication tank. As soon as it is full, the sluice valve connecting the pre-lubrication tank to the pump should be closed. As the tube well may pump sand for the first few minutes, the entry of water into the pre-lubrication tank should not be allowed during this period.

Maintenance of Vertical Hollow-Shaft Motors

Generally burning of the motor take place due to over-heating. Over-heating may result from

1. overloading of the motor,
2. too high or too low voltage,
3. fluctuations in frequency of the current,
4. too much grease in bearing housing,
5. dirt or foreign matter in air gap, and
6. poor ventilation due to air passage being blocked.

If the motor has been out of use for some time, it might be necessary to remove the caked-up grease and refill with fresh grease. While refilling, avoid overfilling the bearing housing as, otherwise, over-heating may result. Take care that no dirt or moisture enters the bearing during the refilling.

For motors in operation, grease should be changed once every six months or after 2000 hours of operation, whichever occurs first. To change grease, the motor is run for about 15 minutes. When bearings are still hot, the drain plug is opened and fresh grease filled through the nipple with a grease gun. The fresh grease is pressed in, till all the old grease has been replaced, as will be evidenced at the drain plug by the new grease flowing out. After new grease has been filled, the motor is run for about 5 minutes, without closing the drain plug, so that excess grease flows out. The motor is then stopped and the drain plug closed.

Lubrication of Vertical Belt-Drive Head

Lubrication of the vertical belt-drive head is carried out by changing the oil once every 500 hours of operation. To change oil, the pump is run till the oil is hot. The filter pipe is turned upside down and the plug opened. All the oil is allowed to flow out. The straight side of the filter pipe is then turned up and filled with fresh oil to the top. The plug is then closed.

Lubrication of Gear Drives

The bearings of gears are oil-lubricated. The oil is circulated by an oil-pumping unit provided in the gear drive. The gear drive should be checked periodically to ensure that oil is circulated properly. This can be done through the window in the gear housing. Should circulation appear to be lagging, the oil level and the condition of the oil in the drive should be checked. Oil tends to thicken with use and will not circulate properly in the gear-drive oiling system.

To change oil, the pump is run till the oil is hot. The drain plug is opened and the oil allowed to flow out. When all the old oil has been drained out, the drain pipe is plugged and new oil poured till it brims over the filter pipe. The filter pipe plug is then closed.

Generally, oil is changed once every 1500 hours of operation or every six months, whichever occurs first. The reservoir is flushed with petroleum solvent to remove any acids or other impurities from the gear drive.

Lubrication of Shafts with Flexible Couplings

The lubrication of flexible shaft is simple and easy. Only two points require lubrication:

1. The yokes containing four needle bearings. They are lubricated through a common nipple.
2. The splined split joint is lubricated through an oil hole with a nipple. Generally, lubrication is done after every 500 hours of operation.

11.1.10 Removal, Dismantling and Assembling of Vertical Turbine Pumps

Major overhauling of vertical turbine pumps would require their removal, dismantling and re-assembling. The step-by-step procedure for these operations is as follows:

Removal of Pump

The procedure for removal of the vertical turbine pump is the reverse of its installation. The various steps involved are described below:

1. Remove the cover from the top of the drive head.
2. Unscrew the round head locking screw and remove the adjusting nuts.
3. For the right-angle drive head, disconnect the oil cooler tubes.
4. Lift the drive head.
5. Remove foundation bolt nuts.
6. Disconnect the discharge pipe.
7. Disconnect the pre-lubrication tank connection pipe, if fitted.
8. Raise the discharge head and column pipe assembly.
9. If an airline gauge is fitted, remove the airline pipe.
10. Raise the discharge head assembly and column pipes to a sufficient height to allow the first column pipe coupling and the drive shaft coupling to be unscrewed (Pipe clamps must be placed below couplings when handling column pipes).
11. Subsequent lengths of column pipes are raised and unscrewed.
12. Finally, carefully raise the pump unit.

Dismantling of the Pump Unit

The following procedure may be followed for dismantling the pump unit:

1. Remove the column pipe, oil tube and line shaft from the discharge case, tubing adaptor and pump shaft, respectively.
2. Remove the suction pipe and strainer from the suction case. Remove the plug from the bottom of the suction case.
3. Remove the tube adaptor from the discharge case. While removing, be careful not to damage the pump shaft. The annular space between the tube adaptor and the pump shaft is packed with water-repellent grease. This grease will come out with the tube adaptor (If the pump is water-lubricated, there is no tube adaptor).
4. Disconnect the top intermediate bowl and the middle intermediate bowl. Generally, for pumps upto 20 cm size, the bowls are of the screwed type and can be disconnected using two chain tongs. For pumps of size 25 cm or more, the bowls are connected by cap screws. To disconnect, remove the cap screws from the connecting bowls. Do not unscrew or remove the cap screw connecting the top intermediate bowl to the discharge case, as these two parts have a combination bushing which should not be separated in the field. These bushings are press-fitted in position in the factory.
5. After the top intermediate bowl has been unscrewed or freed from the middle intermediate bowl, pull the top intermediate bowl along with the discharge case, as one unit. Care must be taken not to let the assembly rest on the pump shaft or damage the shaft in any way.
6. To remove the top impeller, pull the pump shaft out by hand, as far as it will go. Insert the lock collet hammer, the bigger-diameter end facing the impellers. Strike, with the help of the lock collet hammer, the hub of the impeller, driving the impeller downward but holding the pump shaft at the highest position (pulled out to the maximum). This will loosen the lock collet. Remove

it and the impeller from the pump shaft. If the lock collet is hard to remove, insert a chisel or the end of a screw driver in the opening of the lock collet so as to loosen it from the pump shaft.

7. To remove the next intermediate bowl and impeller, repeat steps 4, 5 and 6 listed above.
8. To remove the bottom-most intermediate bowl, uncouple or remove the cap screws, as the case may be. Pulled the bowl off. The pump shaft can be pulled out of the suction case with the bottom impeller.
9. To remove the impeller, strike with the help of a lock collet hammer. The impeller will knock loose. Remove the lock collet with the help of a screw drive.

Reassembling of Vertical Turbine Pump

Once the pump is dismantled, it is overhauled, the defective parts replaced and the pump reassembled, adopting the following procedure:

1. On each pump shaft (of the pump) is marked a pin length, close to its bottom. The distance of this pin length from the bottom will depend on the size and type of the bowl assembly. The pin length determines the position of the bottom-most impeller with respect to the suction case. The position differs in case of semi-open and closed impellers.

(a) Semi-Open Impellers

The pump shaft is inserted in the suction case bearing and made to rest at the bottom. The pin length is made flush with the top of the suction case bearing. The impeller is inserted and the collet locked. The skirt of the impeller and the tapered end of the lock collet must face down. Holding the shaft in position, drive in the lock collet with the help of a lock collet hammer. When the lock collet is firmly driven in, the position of the bottom-most impeller is fixed.

(b) Closed Impellers

The proper alignment is to have the skirt of the impeller flush with the pin-length mark. Insert the impeller and the lock collet on the pump shaft, the skirt of the impeller and the tapered end of lock collet facing down. Lock the impeller by hand, with the lock collet slightly above the pin mark. Drive in the lock collet with the help of a lock collet hammer. When the lock collet is firm, the bottom skirts of the impeller is in flush with the pin. If not, remove the impeller and repeat the process until it is achieved. Insert the pump shaft in the suction bearing and let the impellers rest on the bowl seat. Grease is filled in the suction case bearing before inserting the shaft in position. In order to keep the pump shaft in the desired position, a short piece of threaded rod may be inserted in the hole provided for the plug at the bottom of the thick suction case. This rod will screw into the shaft and can be locked in position with two nuts and a washer on the outer side.

2. Insert the bottom-most intermediate bowl over the pump shaft and secure it to the suction case, either by screwing or with the help of cap screws.
3. The impeller and lock collet are placed over the pump shaft. Before driving the lock collet into position, push the pump shaft down, by hand, to the lowest position. Drive the lock collet with the help of a lock collet hammer (the smaller diameter end of the hammer facing down). While driving the lock collet, it should be ensured that the pump shaft does not move.
4. Repeat processes 2 and 3 till the top impeller has been put in position and the lock collet driven in.

5. Erect the top intermediate bowl-cum-discharge case assembly over the pump shaft and secure it to the middle intermediate bowl.
6. Screw the tube adaptor to the discharge case screw bearing. Before inserting the tube adaptor, it should be ensured that it is packed with grease. If not, put in fresh grease.
7. Remove the rod used at the bottom of the suction case. Press in fresh grease till no more grease can be added. Close the hole using a plug and tighten it in position.
8. Check the projection of the tube and shaft above the column seat. To do this, press the pump shaft down as far as it will go.
9. Check end play of pump. End play is the distance moved by the pump shaft from the bottom-most to the top most position. End play depends on the size of the bowl assembly and is specified by the manufacturer.
10. Check the freeness of the pump shaft by rotating it. If the pump shaft does not bind, the pump is ready for installation.

11.2 SUBMERSIBLE PUMPS

A vertical turbine pump close-coupled to a small diameter submersible electric motor is termed a submersible pump. The motor is fixed directly below the intake of the pump. The pump element and the motor operate while entirely submerged. Such an installation eliminates the long vertical shaft in the column pipe. The performance characteristics of the submersible pump are similar to those of the vertical turbine pump. The efficiency of the pump is increased by the direct coupling of the motor, and its effective cooling by submergence in water.

The principal advantage of the submersible pump is that it can be used in very deep tube wells where a long shaft would not be practical. These pumps are also less affected by deviations in the vertical alignment of the well. As the submersible pump has no above-ground working parts, it can be used where flooding may be a hazard. It is also adaptable to locations like public grounds where an above-ground house would be inconvenient. A submersible pump can be installed in a well of inside diameter as small as 10 cm. Its main limitation is that it cannot be operated by an engine; its use being limited to places where electric power is available.

11.2.1 Constructional Details

The submersible pump consists of the pump bowl and electric motor assembly, a discharge column, head assembly and a water-proof cable to conduct current to the submerged motor. The sectional view (schematic) of a submersible pump showing the details of parts is shown in Fig. 11.17.

Submersible Electric Motor

The submersible electric motor has the same diameter as the pump bowl. It is much longer than an ordinary motor of the same horse power (Fig. 11.18). It is a squirrel-cage induction motor which may be of the dry or wet type. The dry motor is enclosed in a steel case filled with a light oil of high electric strength. A mercury seal, placed directly above the motor armature, prevents oil leakage or water entrance at the point where the drive shaft passes through the case of the impeller. *Wet motors* are those in which the well water has access to the inside of the motor, with the rotor and the bearings actually

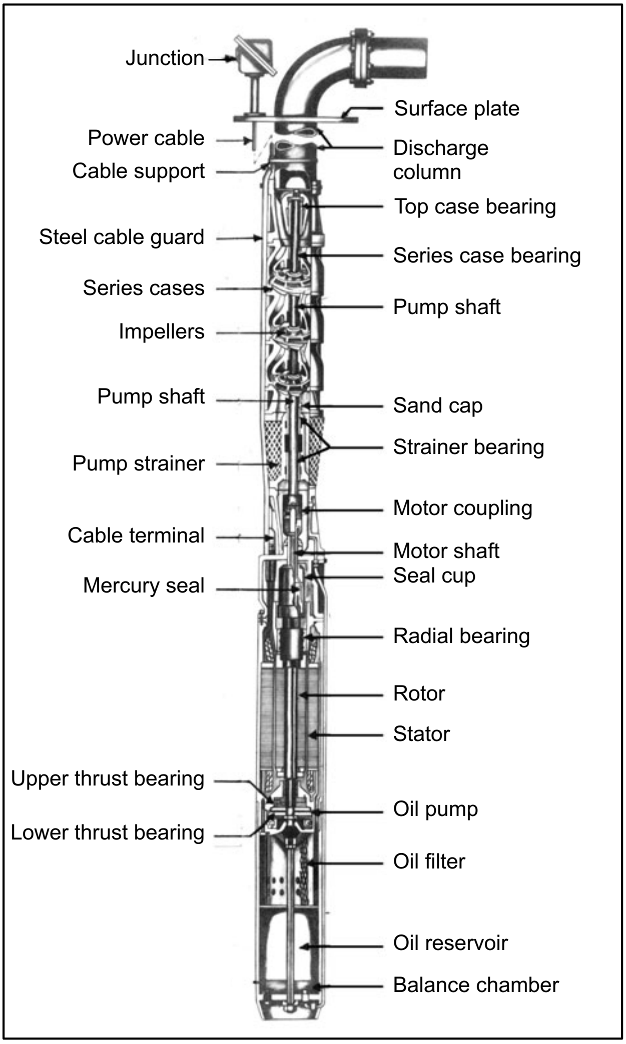


Fig. 11.17 Sectional view (schematic) of a submersible pump showing parts

operating in water. In this type of motor, the windings of the stator are completely sealed off from the rotor by means of a thin stainless steel inner lining. A filter around the shaft is required to prevent the entry of abrasive material into the motor. The wet-type motor should be filled with water during installation so that the bearings will have sufficient lubrication when the motor is first started.

The stator windings are continuous for the whole length of the motor. The rotors are made in sections on a continuous shaft, with bearings between them to guide the shaft and maintain the correct alignment. The electric cable leading from the motor to the switch board at the ground surface is waterproofed and placed outside the discharge pipe.

Pump Elements

Submersible pumps are multi-stage centrifugal pumps fitted with radial-flow or mixed-flow impellers. Pumps with radial-flow impellers are used for low capacities and high total heads, and those with mixed-flow impellers for medium capacities and medium heads. The impellers are dynamically balanced and all the pumps bearings are water-lubricated and protected against the ingress of sand and other suspended particles. The pump suction casing between the pump and motor is guarded by a perforated strainer to prevent the entry of any suspended materials in the water. An exploded view of the pump element is shown in Fig. 11.19.

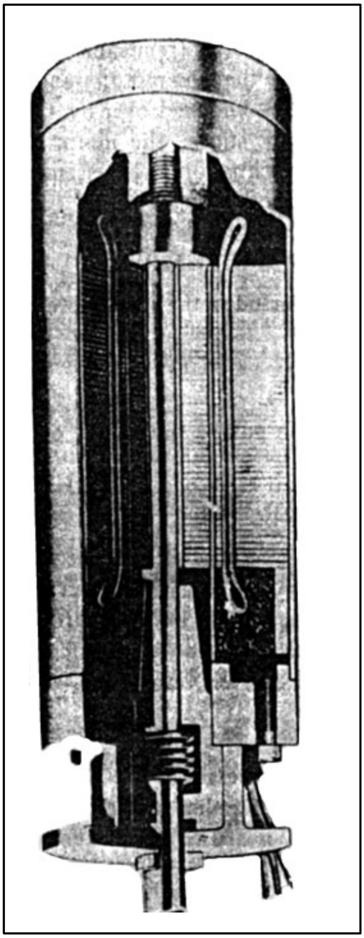


Fig. 11.18 Cut-away section of a submersible electric motor
Courtesy: Johnston Pumps (India) Ltd., Kolkata (1968a)

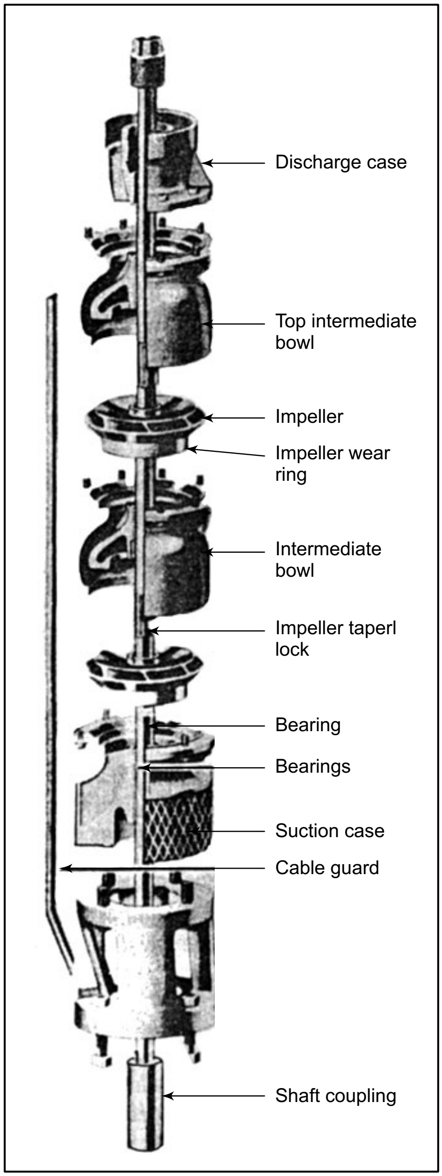


Fig. 11.19 Exploded view of the pump element of a submersible pump
Courtesy: Johnston Pumps (India) Ltd., Kolkata (1968a)

Discharge Column and Head Assembly

The discharge column consists of a discharge pipeline connected to the pump element. The discharge pipe is supported at the ground level with a supporting clamp which rests on a solid foundation. A pressure gauge is sometimes fixed to the bend on the delivery pipe to indicate the total operating head. The delivery pipe is usually provided with a sluice valve to regulate the flow. The power cable is connected to a switchgear fixed to a switchboard. The switchgear is usually of the oil-filled type, and comprises three-phase contactors and an automatic star-delta starter.

11.2.2 Storage and Preservation of Submersible Pumps

If storage is for a short period (< 2 weeks), the pumping set can be stored standing vertically, keeping the surroundings protected from dust and frost. However, if the pumping set is to be stored for prolonged periods, the pump should be disconnected from the motor. Thereafter, the pump and the motor should be stored vertically in a dry, dust-free room (the pump can stand on its head, if desired). Before re-connection of the pump to the motor, ensure the both pump and motor shafts can be easily rotated by hand. Should the pump rotor stick, despite the precautions taken to preserve it, the pump must be stripped once more to loosen the rotating parts. Should the motor stick, an attempt can be made to loosen it by filling it with water, connecting it to the electricity mains (remember to earth it), and switching it on for an instant. Make sure that the motor stands square on the ground before switching on, and is not knocked over by the torque (hold on to it if possible). If the rotor still sticks, the motor should be tested separately from the pump, as any switching on after assembly to the pump would damage the pump bearings (dry running).

11.2.3 Installation of Submersible Pumps

The installation of a submersible pump includes the initial preparations, installation and testing.

Initial Preparations

Before starting the actual installation of the pump, the initial preparation to be made are as follows:

(i) *Condition of the Well*

Before installing the pumping set, it should be ensured that the well is fully developed and the discharge water is free of sand. The water level and drawdown should be ascertained. The well should be tested for its alignment. A slight inclination of the bore hole is unimportant, but a crooked section can make the installation difficult or even impossible.

(ii) *Checking of Equipment*

Unpack and examine the pumping set and accessories for any damage or shortage. Generally, packing instructions are supplied by the manufacturers. Examine the cable for damage particularly near the pump. The cable must be carefully handled at all times, and should not be pulled, twisted, dragged over sharp stones, or run over by wheeled traffic. Above all, the cable should never be allowed to carry the weight of the unit.

Test the motor for continuity and insulation resistance by means of a Megger, to ensure that it has not been damaged in transit. The insulation resistance should exceed 10 megohms.

(iii) *Filling the Motor with Fresh Water*

Submersible motors have water-lubricated plain bearings and must never run dry. Even testing the motor for a short period out of water must be avoided, as it may cause damage to the bearings. Before installing in the well, the motor must be filled in an upright position, with clean water free of sand and acid. Two plugs are provided for filling the connecting piece or inlet of the motor—the one to close the filler opening and the other to close air-escape opening. On earlier designs, these two plugs were partly installed in the suction body of the pump, at different heights. The funnel which is supplied with every pump should be used for filling. Its threaded end is stepped off in three sections, one or two of these should be cut off to fit the end of the funnel to the diameter of the filler opening.

When the motor has been filled with water, it should be left for about 30 minutes, with the two holes open to allow air bubbles trapped in the winding to escape. This process is assisted by gently moving the motor to and fro. It then becomes necessary to top up with a little more water. After the filler and air-escape openings are closed, the motor is ready for operation and the unit can be installed.

Equipment Required

For installing the pump, a reliable lifting gear is required, e.g. a crane or a tripod with a chain pulley block of sufficient capacity.

Installation Procedure

The installation procedure varies according to the size of the submersible pump unit. Usually, the steps involved are as under:

The first step is to clamp, at a convenient height, one of the pairs of supporting clamps (supplied with the pump), to the first length of the riser pipe. The riser pipe is then connected to the discharge branch or check valve on the pump. By means of the tackle, the pump is then slowly lowered into the well until its weight is taken by the supporting clamps resting on two parallel mild-steel channels or wooden beams of adequate dimensions, placed in position across the top of the well to act as bearers. The tackle of the pulley block is then detached. Another length of pipe is provided with the second pair of supporting clamps. The pipe is lowered slowly, using the chain pulley block (Fig. 11.20) connected to the first length of pipe, and attached to the tackle. The first pair of supporting clamps can then be removed, transferring the weight of the assembly on to the tackle, by means of which the pump and piping assembly is slowly lowered until the weight is taken by the second pair of clamps. The operation is repeated for each length of the column pipe until the desired depth is reached.

The threaded pipe sections must be tightly screwed and, if necessary, a locking device fitted so that the pump unit cannot fall into the well through one of the pipe getting unscrewed during pump operation. It must be remembered that, while switching on and off frequently, a twisting movement is exerted on the column pipe.

During installation, a pair of clamps must always be firmly attached to the riser pipe so that, in the event of failure of the lifting gear, the pump cannot fall into the well.

The depth at which the pump is installed should be such that the top flange of the pump is at least 50 cm below the lowest level of water in the well. This level is reached after the pump has been running for a prolonged period with the valve fully open.

Fig. 11.20 Installation of a submersible pump in a tube well. The motor and pump assembly is being hoisted for lowering into the tube well

Attaching the Cable to the Riser Pipe

Care must be taken never to subject the cable to any strain while the pump is being installed. When the column pipe is in lengths not exceeding 4 m, the cable is attached to the pipe by a clamp immediately above and below the flange or socket joint. If the length exceeds 4 m, it is advisable to use an extra clamp for the cable, halfway between those at the joints. Clamps may be band type or clip type.

Band-type cable clamp (Fig 11.21). This is used for small flat cables of sizes ranging from 2×1.5 mm^2 to 3×6 mm^2 and consists of a rubber band and two plastic buttons. A rubber band of a specific length with respect to the pipe size, with two buttons fixed in it, is to be clasped to the pipe so that the smaller end

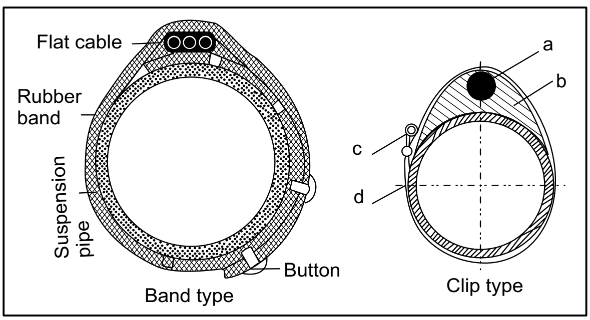


Fig. 11.21 Types of cable clamps for attaching the power cable to column pipes of submersible pumps

of the rubber band is below the flat cable. The band is then pulled around the pipe until the buttons can be fitted. The flat cable must be pressed firmly to avoid slip-off.

Clip-type cable clamp. This type of clamp is used for flat or round cables of size 3×10 mm^2, and consists of a cable protector *b* (Fig. 11.21) wrapped around a cable *a* and secured to the pipe by a metal strap. End *d* of the strap is passed through the buckle and bent back. The free length of the cable is then turned twice round the pipe and the cable protector. Finally, end *c* is secured in the buckle screw. The strap is then tightened by turning the screw.

In order to prevent the cable from slipping due to its own weight, the clips must hold it firmly in place at each length of the pipe.

Depth of installation

To ensure that the unit is installed at the correct depth, a careful record must be kept of the exact length of the rising main installed. Alternatively, the total length of piping may be cut off beforehand. The unit should be suspended 2 to 3 m above any layer of silt at the bottom of the well or borehole. Fig. 11.22 shows submersible pump installed in a tube well.

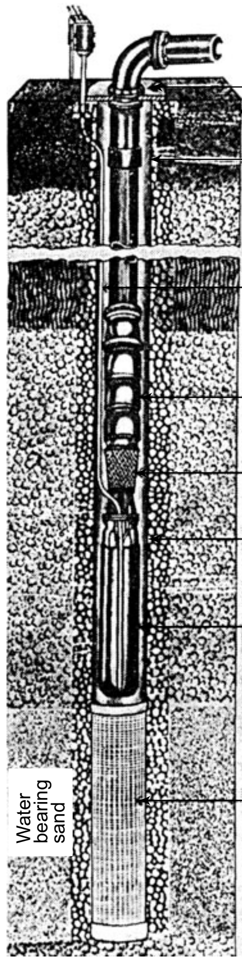


Fig. 11.22 Schematic illustration of a submersible pump installed in a tube well

Connecting the Motor

This must be done by a qualified electrician. Circuit diagrams for motor connection are supplied by the manufacturers. The protective switch is always set to the full load current during pumping. The main switch and fuses are installed so that the entire installation can be isolated from the power supply at any time.

The earthing requirement for submersible pumps may vary with different electricity authorities, but the following provisions should be acceptable in most cases:

1. The pipe clamps at the top of the borehole or well must be galvanized or otherwise treated so that they are not subject to corrosion.
2. A brass earthing clip is provided on the delivery pipe clamp, for attaching the earthing conductor, for safety against weather elements.
3. The earthing conductor is to be protected from mechanical damage, from its point of connection at the earthing clip to its entry into the switchboard.

The overground installation is shown in Fig. 11.23.

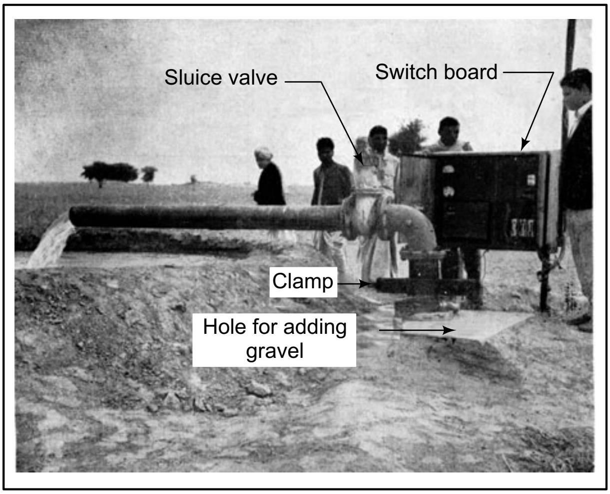


Fig. 11.23 Overground view of the installation of a submersible pump in a tube well

11.2.4 Operation of Submersible Pumps

Before operating the pump, the direction of rotation is checked. To ascertain the correct direction of rotation, let the motor run in both directions with the stop valve closed. The direction of rotation is changed by interchanging two of the phases. The pressure gauge will show different readings for the two directions. The direction which gives the higher pressure is the correct one. When running freely the correct direction of rotation can also be judged from the amount of water pumped.

Starting and Initial Run

The pump is started with the sluice valve closed or slightly open. During the initial run, it is checked as to whether the pumped water is clear or muddy and whether any impurities are being pumped. If the water contains sandy or gritty particles or other impurities, care is taken not to stop pumping, otherwise the particles will settle down inside the pump and on top of the non-return valve (if fitted), and may choke or seize the pump. The pump must be run with the valve not fully open (at not more than 40 per cent discharge), until the sand content falls. The valve is then opened slowly to its full extent. Pumping is continued in this manner until it is possible to pump with a fully-open valve, without pumping excess sand. Generally, the permissible limit is up to 25 grains of sand per cubic metre of water (0.001 per cent, on volume basis, or 0.0025 per cent by weight). When the pumped water is clear, the pump may be stopped and restarted as required.

Shut-down Periods

The pump should not be allowed to remain stationary for more than 14 days at a stretch as, otherwise, lime, iron and other substances tend to settle in the bearings and impeller gaps, and block the pump rotor. If operating conditions require the pump to remain stopped for a longer period, it should be started and allowed to run for at least 5 minutes once every 14 days and preferably once every 8 days. Only then the pump will be ready for instant resumption of service at any time.

11.2.5 Common Causes of Breakdown of Submersible Pumps

The most common cause of breakdown of submersible pumps is the burning of motors. The following are the common causes of burning of the motor, and the remedies:

1. *Formation of Insulating Layer*

If the temperature of the winding exceeds the maximum allowable limit, it may result in the burning of the motor. This is generally caused by formation of an insulating layer around the motor surface, due to silt or grit gathered on the motor frame. The burning in this case is uniform. Whenever the motor is taken out, the surface should be cleaned and repainted before lowering.

2. *Overloading*

A power overload occurs when the pump requires more power from the motor than the rated motor output. Such a situation could lead to the overloading of the winding, thus burning the motor. Power overloads can occur if the pump is run far away from the duty point specified on the pump and motor. In the field, such conditions normally happen if the assessment of total head to be developed by the pump is not made properly. To avoid this, the motors selected should have adequate output.

3. *Voltage Fluctuation*

Submersible motors are designed to function without any problem, in the voltage range of ± 10% of the rated voltage. When the voltage exceeds the limit, the output of the motor increases, leading to overheating and burning of the winding.

It is always advisable to have a voltmeter and an ammeter fixed on the switchboard as near the motor as possible. Necessary action could then be taken, in case the variation in voltage is more than the permissible limit.

It is safer to have a motor of horse power about 10 to 15 per cent more than the rated power for the pump, so that some overload can be sustained. In case of fluctuating voltage conditions, a 3-phase voltage stabilizer should be provided.

4. *Single Phasing*

Single phasing of the motor is frequent in the field. In most cases, the missing of a phase can also be due to the malfunctioning of the switchgear. Inadequate capacity of fuses can also lead to this hazard.

Further, single phasing can occur due to damage of the power cable. This can happen at the time of pump installation. Great care must be taken to avoid any damage or bending of the cable at the time of installation of the pump set.

It is recommended that economy should not be considered in the choice of switchgear for quality and capacity. It is always advisable to have a single-phasing preventer installed with the pump set.

5. *Excessive Number of Starts*

The starting current of all motors is much higher than the current required for normal running. Consequently, if the number of times the pump is started is high and in quick succession, the winding will not have time to dissipate the heat developed in starting and will overheat. This will weaken the insulation and result in the windings burning. The permissible switching frequency depends on the motor horse power. The maximum switching allowed is 20 times and 15 times an hour for motors upto 5 hp, and 7.5 to 100 hp, respectively. If the motor does not start to run and build up to full speed as soon as it is switched on, it must be switched off immediately and should not be started again until about 5 minutes have elapsed.

6. *Electric Discharge*

Electrical discharge can occur between winding and earth or between turns. The cause can be direct sparking or accidental jumping of current from one conductor to another. The contact between winding and earth, due to defect in insulation of the wire or puncture of the wire at the time of winding, could also cause the damage.

7. *Wrong Repair and Replacement*

The spare parts used in the repair of motor, starter and pump may be of improper quality and capacity, which may cause burning of motor due to non-matching of characteristics. The parts replaced should be genuine, purchased from authorised dealers of reputed manufacturers.

In addition to burning of submersible motor, the following are the other causes responsible for breakdown of submersible pumps:

1. *Damage to Motor and Pump Parts*

The submersible pump and motor unit is aligned by the manufacturer or in repair workshops. Rough handling in transportation and carriage to the site of installation may cause misalignment which will be noticed only after lowering of the unit. Misalignment may cause vibrations leading to damage to motor and pump parts, and overloading of motor resulting in the burning of the windings.

The motor and pumps should be assembled and checked for free movement in the shop, and packed in wooden container of size matching the equipment. The box should be carried carefully to the site and should be opened only at the time of lowering.

2. *Heavy Fine Sand Pumping*

Submersible pumps will provide long service life if the sand content of the water is limited to 28-40 ppm. With sand pumping, the service life of the pump is reduced drastically. Sand in water damages the rubbing surfaces of the neck ring and impeller and causes more clearance. Too high a clearance results in high vibrations which reduce the discharge and overload the motor. Vibrations disturb the motor alignment and ultimately burn the motor.

3. *Loose and Eccentric Column Pipe*

A loosely bolted and non-rigid column pipe to which a submersible pump is attached can cause vibrations in the whole system. These vibrations will ultimately damage the pump due to misalignment and lead to the breaking of the motor or its burning.

Flanges and other types of joints must be properly matched and tightened with an ordinary nut and a check nut. The pipe should be kept at the centre of the housing and on one side.

4. *Fallen Pumps and Motors*

The falling down of pumps and motors is due to vibrations, and faulty repair, i.e. non-replacement of worn-out studs and water hammer. Fishing is easier with a fallen pump than a detached motor. For fishing the fallen motor, the manufacturer should be asked to provide a mechanical clamp from the bottom of the motor to the discharge nipple over the non-return valve, which can be attached to a wire rope. This wire rope should be brought up to the top of the well so that in case of an accidental fall, the motor can be easily pulled out. This will not only save the motor but the well itself because, many a time, the well is abandoned because of the failure to fish out the motor.

5. *Seizure of Pump or Motor Bearing*

Seizure of the pump bearing can result when the pump runs dry. This can happen due to a fall in water level during summer or over pumping of the tube well. The pump can be safeguarded from dry running by installing a pneumatic water level indicator, observing it periodically and extending the column pipes to cater to a situation of falling water, if required.

11.2.6 Common Troubles in Submersible Pump Operation and their Remedies

The following are the common troubles experienced in the operation of submersible pumps, their possible causes and remedies.

1. *Pump Fails to Start*

This may be due to blown fuses, short circuiting or a heavy load on the pump.

Remedies will include precise testing, diagnosing the trouble and taking remedial measures. The procedure to be adopted is given below (to be done by an accredited electrician only).

(i) Note the colours of the cores of the motor cable and the terminals to which these are connected. Disconnect the cable from other equipment.

(ii) Test the insulation resistance of the motor cable and cable joint. Connect one lead of a Megger tester to the rising main and the other lead to the red core of the motor cable. A reading of 2 megohms or more indicates that the motor winding, cable and cable joints are sound. If the reading is less than 2 megohms, the fault is either in the wiring or the pump is locked by sand or other foreign substances.

(iii) Check the above-ground wiring against the wiring diagram. Test the operation of all the above-ground electrical equipment, with the motor cable disconnected. If the operation of the equipment is normal, reconnect the motor cable, close the gate valve and reopen it three-quarters of a turn only. Switch on the motor. If the overload-release device trips or other faults occur, it is an indication that cable connections are wrong or the pump is sand locked. Try to reverse the direction of rotation for about three seconds only. If the pump still does not start, it must be raised to the surface to be cleared of obstructions.

(iv) If the pump is sand locked, recheck the level at which the pump suction is set. The pump suction and the motor base must be in the solid casing (pump housing) and not opposite the well screen.
(v) Ensure that the fuses are of the correct capacity and in good order.
(vi) Check that the line voltage is within permissible limits. If an engine-driven alternator is supplying the power, ensure that the supply frequency is correct.

2. *Pump Starts but the Discharge is Low, or there is No Discharge at All*

The following may be the reasons:

(i) The motor is running in the reverse direction.
(ii) The pump is operating against a head greater than its rated capacity.
(iii) The pump suction is blocked by foreign matter, salt deposits or collapse of the bore.
(iv) The pump is air-locked (no discharge at all).
(v) The reflux valve above the pump is jammed or the riser pipe closed by obstruction or by the valve.
(vi) Voltage or frequency is considerably lower than required.
(vii) Inadequate bowl assembly submergence.

The following tests should be carried out to diagnose the causes and suggest required remedies:

(a) Close the gate valve at the surface completely. Check the pressure gauge reading, ammeter reading, and the distance from the centre of the pressure gauge dial to the water level in the well.
(b) Compute the total head by adding the pressure gauge reading and the distance from the centre of the pressure gauge dial to the water level in the well. The total head obtained should be approximately the same as expected.
(c) Check the line voltage in all the phases while the pump is in operation. If power supply frequency variations are even remotely possible, this should be checked (A reduction from 50 cycles to only 49 cycles will result in a noticeable decrease in discharge). It is always advisable to have a single phasing preventor installed with the pumpset.

If the tests resulting from (a), (b) and (c) above show that the pump is performing normally at no discharge, the direction of rotation is correct. However, if on opening the gate valve, the ammeter reading does not change noticeably, there is either a blockage in the system, the pump is operating against a head greater than the design head, or the pump is air-locked.

If the discharge from the pump is into an elevated reservoir or tank, separate the pipe system at the ground level immediately after the gate valve at the ground surface, and check the motor current and discharge rate obtained at this point. An increase in discharge and motor current under these conditions will prove that the trouble is in the system beyond the gate valve and not in the pump or system below ground level. An air locked pump will result in a lower-than-normal reading of line current, without any discharge at all. Whether the gate valve is opened or closed, disconnecting the surface piping system beyond the gate valve will not make any difference in the ammeter reading and the pressure gauge reading will remain zero.

3. *Pump Runs and Discharges Steadily but the Discharge is Below Normal*

This may be due to

(i) fault in power supply,
(ii) mechanical friction in pump or motor,

(iii) riser pipe developing a hole or a leak developing in the system below the ground level
(iv) the pump being worn by sand, there is an increase in mechanical friction,
(v) partially plugged inlet/impeller,
(vi) excessive lift.

The investigations to identify the trouble will be as follows:

(a) Close the gate valve at the ground surface for a sufficiently long time, to check the ammeter and pressure gauge readings. Check the water level in the well.
(b) Calculate the closed valve head developed by the pump, as per procedure laid down in item 2 above. If this value is considerably less than the design total head, whilst the ammeter reading is higher than that specified by the manufacturer on the test sheet, the existence of faults (ii), (iii) and (iv) are confirmed. The pump, motor and piping must then be withdrawn from the well for examination and repair.

4. *Pump Runs and Discharges Intermittently and Air Bubbles are Present in the Discharge*

This means that the pumping rate is greater than the rate of recuperation of the well. If allowed to persist, this may cause damage to the pump, shaft keys, couplings and motor.

The test procedure will include closing the gate valve at the surface completely and then opening one turn only. If the trouble is corrected, this proves that the pump discharge is too high for the yield of the well.

If the trouble persists, close the gate valve further, a small part of a turn at a time, until the trouble ceases. Leave the gate valve set and tighten the gland nut on the gate valve stem. Remove the gate valve handle to prevent unauthorised interference.

5. *Pump Vibrates or is Noisy*

This may be due to

(i) bent bowl shaft,
(ii) crooked well,
(iii) partially plugged bowl or impeller,
(iv) impeller(s) not balanced,
(v) bent motor shaft,
(vi) worn bearings in motor,
(vii) pump is cavitating.

6. *Pump Draws More Power than Required*

This may be due to

(i) excessively tight bowl assembly,
(ii) change in pump settings,
(iii) incorrect number of stages or impeller trimming,
(iv) wrong bowl assembly (new pump),
(v) excessive flow rate,
(vi) cascading water (causing air entrainment).

The remedies, in general, are evident from the causes of the troubles.

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SHORT QUESTIONS

I. State True (T) or False (F).

1. Deep well turbine pump is not adapted to seasonal fluctuations in water level in the well.
2. Submersible pump can be driven with an electric motor or an engine.
3. If two impellers are of the same diameter, the one having a greater width will have a greater capacity.

4. In a multi-stage centrifugal pump, the same amount of water passes from stage to stage.
5. The efficiency of semi-open impeller is higher than enclosed impeller.
6. Turbine pumps cannot operate at a high efficiency, over as wide a range of speed, as can volute pumps.
7. When the pumped water contains fine sand particles, water-lubricated pumps are preferred.
8. Oil-lubricated pump is preferred, where pump has to stand idle frequently for considerable time.
9. The V-belt drive is the least efficient of all the types of drives.
10. In vertical turbine pump, looking from the top, the direction of rotation of electric motor should be clockwise.
11. In water-lubricated vertical turbine pumps there is no shaft enclosing tube.
12. For similar operating conditions the efficiency of submersible pump is more than vertical turbine pump.
13. Vertical turbine pump is adaptable to locations where flooding may be a hazard.
14. Submersible pump cannot be operated by an engine.
15. The submersible electric motor is much longer than an ordinary motor of same horse power.
16. In submersible pumps mixed flow impellers are used for low capacities and high total heads.
17. The direction of rotation of a submersible pump can be changed by interchanging of two of the phases.
18. Submersible motors can function without any problem in the voltage range of ± 20 per cent of the rated voltage.
19. To avoid burning of windings, the maximum switching frequency allowed for motors upto 5 hp is 20 times per hour.
20. A submersible pump can be lowered to any depth for pumping water.
21. In a submersible pump, the impeller is not surrounded by diffuser vanes.
22. Submersible pump is a centrifugal pump.

Ans. True: 3, 4, 6, 8, 11, 12, 14, 15, 17, 19, 20, 22.

II. Select the correct answer.

1. In case of submersible pump set, the motor is
   (a) completely submerged in water (b) partially submerged in water
   (c) not submerged in water (d) kept on the ground surface
2. An impeller with large ratio between the diameter of the eye of the impeller and the impeller diameter, would be a
   (a) high-capacity pump with lower head
   (b) lower-capacity pump with higher head
   (c) lower-capacity pump with lower head
   (d) high-capacity pump with higher head
3. Turbine pump horse power requirements increases as the
   (a) square root of the speed (b) speed
   (c) square of the speed (d) cube of the speed
4. The most efficient method of transmitting power from horizontal prime mover to vertical turbine pump is
   (a) right-angle gear drive (b) quarter-twist V-belt drive
   (c) quarter-twist flat belt drive (d) quarter-twist chain drive

5. The rated horse power of the submersible motor should be __________ per cent more than the rated power of the pump to sustain some over loading.
   (a) 5 – 10 (b) 10 – 15
   (c) 15 – 20 (d) 20 – 25
6. A submersible pump in a 100 m deep drilled well is under 10 m of water. The top of well is 1 m below the ground surface. How much is static head present?
   (a) 10 m (b) 11 m
   (c) 100 m (d) 101 m
7. Which of the following pumps definitely does not need priming?
   (a) jet pump (b) centrifugal pump
   (c) submersible pump (d) radial flow pump
8. What is the function of each stage in multi-stage turbine pump?
   (a) add volume capacity (b) add pressure head capacity
   (c) decrease brake horse power requirements
   (d) increase efficiency
9. Submersible pumps are
   (a) jet pumps (b) mixed flow pumps
   (c) propeller pumps (d) multistage centrifugal pumps
10. What could cause a submersible pump to take too much power?
    (a) circuit breaker tripped (b) crooked well
    (c) incorrect number of stages or impeller trimming
    (d) pump is air-locked

Ans. 1. (a) 2. (b) 3. (d) 4. (a) 5. (b) 6. (a) 7. (c) 8. (b) 9. (d) 10. (c)

12

Propeller, Mixed Flow and Jet Pumps

Propeller pumps are efficient for application under high discharge and low head situations, while mixed flow pumps are superior under medium head and high discharge situations. Conventional volute centrifugal pumps are usually efficient only at heads more than about 6 metres. Jet pumps are adapted to situations of high suction head and low well yield, where the prime mover is to be located at the ground surface. They are popular in domestic water supply.

12.1 PROPELLER PUMPS

A propeller pump is specifically adopted to high discharge low head pumping. It is most suitable to lift water from canals, rivers and streams and in dewatering schemes. It has high efficiency under low heads, specially within 2 metres. It can be used as portable units operated by light weight engines or in permanent installations using electric motor or engines. Portable engine operated propeller pumps have become very popular in the rice growing regions of south-east Asian countries. They have immense potential for adoption in the delta regions and canal command areas of India and in other countries.

12.1.1 Principles of Operation

Propeller pumps are axial flow pumps in which the pressure head is developed mostly by the propelling or lifting action of the propeller blades on water. The characteristic differences in the principles of operation of the pumping elements of propeller pumps, as compared to radial flow pumps, is illustrated in Fig. 12.1. Radial flow pumps (volute centrifugal pumps/turbine pumps) develop the pressure head principally through centrifugal force. The impeller vanes throw the incoming water radially outward against the casing where the pressure is built up by converting a major part of the velocity energy into pressure energy. On the other hand, a propeller pump develops most of its head by the lifting action of the impeller, with the flow entering axially and discharging nearly axially into a guide case.

Unfortunately, propeller pumps have not become popular in India in irrigation and drainage pumping. The only exception is the *petti* and *para*, used in the backwater areas of Kerala for drainage pumping (Fig. 12.2). It is a propeller pump specially adapted to manufacture by local blacksmiths and carpenters. The pump casing and the discharge spout are made of wooden boards which are joined together and reinforced with iron bands. The spout is box shaped. The metal parts are the propeller,

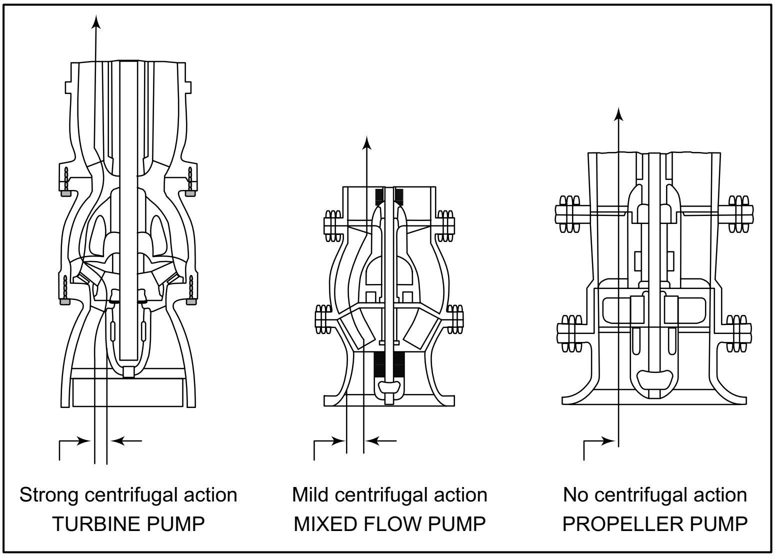

Fig. 12.1 Characteristic difference in the principle of operation of turbine, mixed flow and propeller pumps

line shaft and the drive pulley. The pump, however, is inefficient and requires high energy input. There are only a few firms in India dealing in factory-made propeller pumps. These pumps are manufactured for specified head and discharge ranges. It has been observed that the prices of these pumps are disproportionately high and beyond the capacity of an average farmer. In such a situation the farmers have no other choice but to use the centrifugal pump which is inefficient at low heads. This results in high cost of irrigation or drainage and huge loss of energy.

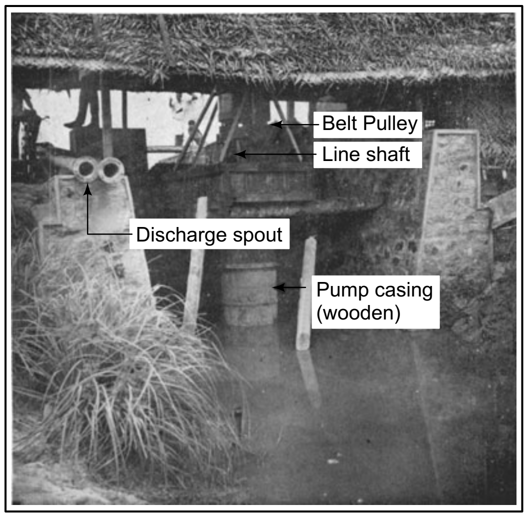

Fig. 12.2 A locally fabricated propeller pump, called *petti* and *para*, commonly used in drainage pumping in the Kuttanad region of Kerala

12.1.2 Construction

Propeller pumps may be oil lubricated or water lubricated. The parts of a propeller pump (Fig. 12.3) may be divided into four sub-assemblies, i.e. propeller and diffuser assembly, pump column, discharge head and pump drive.

Propeller and Diffuser Assembly

The basic elements of a propeller pump are the propeller and diffuser, often forming a distinct bowl assembly (Figs. 12.3 and 12.4). This assembly is submerged under the liquid to be pumped. The bowl assembly comprises

1. a flared suction bell to streamline the liquid flow into the impeller,
2. an open-type, dynamically balanced impeller,
3. a diffuser with guide vanes,
4. an impeller casing,
5. a heavy-duty impeller shaft.

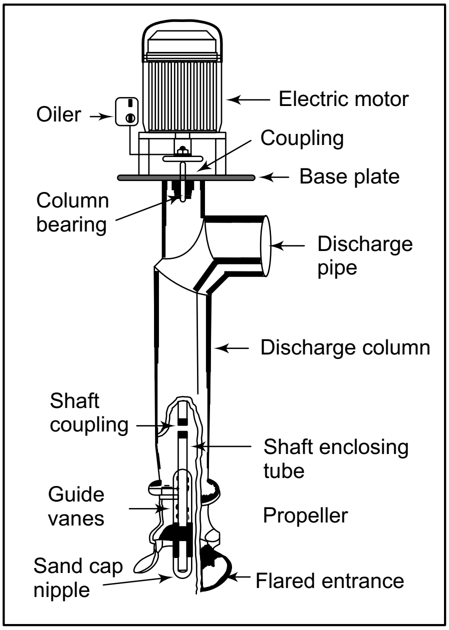

Fig. 12.3 View of propeller pump with the propeller and lower shaft assembly exposed

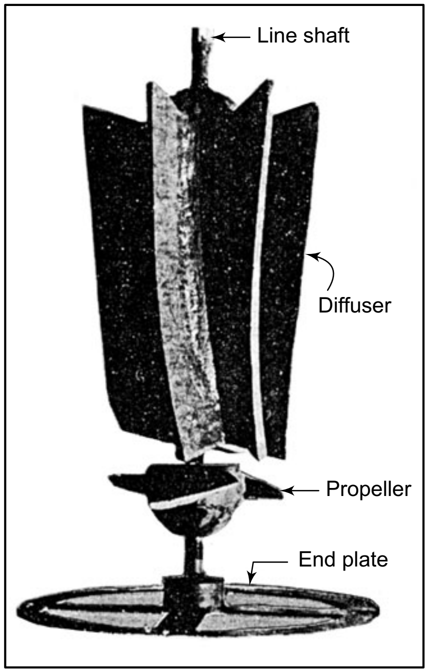

Fig. 12.4 Propeller pump elements

A flared entrance below the propeller is used to reduce entrance losses. The impeller, also known as the propeller, operates in a cylinderical casing which is an extension of the discharge column assembly. The impeller usually has 3 to 6 blades (Fig. 12.5), depending on the design specific speed. The blades are set on the shaft at angles determined by the total head and operating speed of the pump. Sometimes, however, the blades are cast separately and may be threaded to receive a nut for securing them to the hub. With this arrangement, the blade angle may be adjusted to suit operating conditions. The propeller blades are carefully filed and scraped to reduce skin friction. They are keyed to the drive shaft and are accurately positioned by a locking collar and nut. A cone-shaped cover is usually installed over the locking nut to eliminate eddies and prevent the entry of sand or grit into the lower pump bearings. The diffusion vanes smooth out the disturbances caused by the propeller. The propeller is mounted on a suitable shaft.

Column Assembly

The column assembly (Fig. 12.3) of a propeller pump comprises the line shaft which joins the impeller with the driving head shaft. In case of oil lubricated pumps, the line shaft assembly is enclosed in a heavy-duty shaft enclosing tube. Below 400 mm size, the tubes are usually of the screwed type whereas, beyond 400 mm, flange type joints are preferred which considerably facilitate the joining and dismantling of the tube. In case of water lubricated propeller pumps, the line shaft is made of high tensile carbon steel or stainless steel and is usually sleeved with stainless steel at the bearing points to prevent rusting. There are no shaft enclosing tubes as lubrication is with water only. The line shaft is provided with suitable bearings, usually grease lubricated.

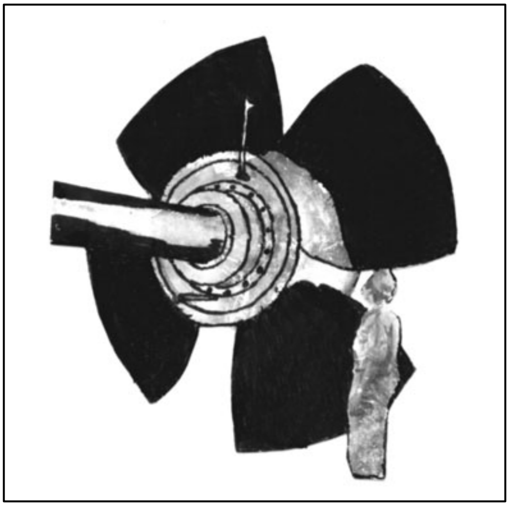

Fig. 12.5 A giant-sized propeller mounted on drive shaft
Courtesy: Embara Mfg. Co. Ltd., Tokyo

Discharge Column

The discharge column (Fig. 12.3) is a combination of a column pipe and delivery bend, and is designed so as to reduce hydraulic losses to the minimum. It is specially machined for accurate alignment. A cover plate is bolted on top of the discharge head. This plate provides a seat to the skirt of the driving head.

Driving Head

The driving head comprises a vertical motor, which may be solid-shaft or hollow-shaft motor, and arrangements for oil lubrication (for oil lubricated pumps). In case of a solid shaft motor, the line shaft assembly and the motor shaft are joined by a set of flexible couplings. The impeller adjusting nut is housed between the two couplings. A thrust bearing is provided below the couplings to carry the combined pump thrust and weight of the rotating parts. In case of a hollow shaft motor, a rigid coupling, similar to the line shaft coupling, replaces the flexible coupling set. An impeller adjusting nut is provided at the top of the motor. The thrust is borne by a thrust bearing located in the top cover of the motor.

12.1.3 Operating Characteristics

A typical performance curve of a single-stage propeller pump is shown in Fig. 12.6. The head-capacity curve of a propeller pump is steeper than that of a centrifugal pump. Its head drops faster with increase in capacity than that of the centrifugal pump. A slight increase in the pumping head causes a large decrease in the quantity of water delivered. Therefore, it is necessary that the propeller pump be operated at the rated head, as far as possible. The brake horse power curve slopes downward to the right, in contrast to that of the centrifugal pump which slopes upward to the right, with a slight downward hook at very high capacities. Thus, the power requirement of a propeller pump is increased as the head is increased and the capacity is reduced, whereas in a centrifugal pump the power required is decreased as the head is increased and the capacity drops down.

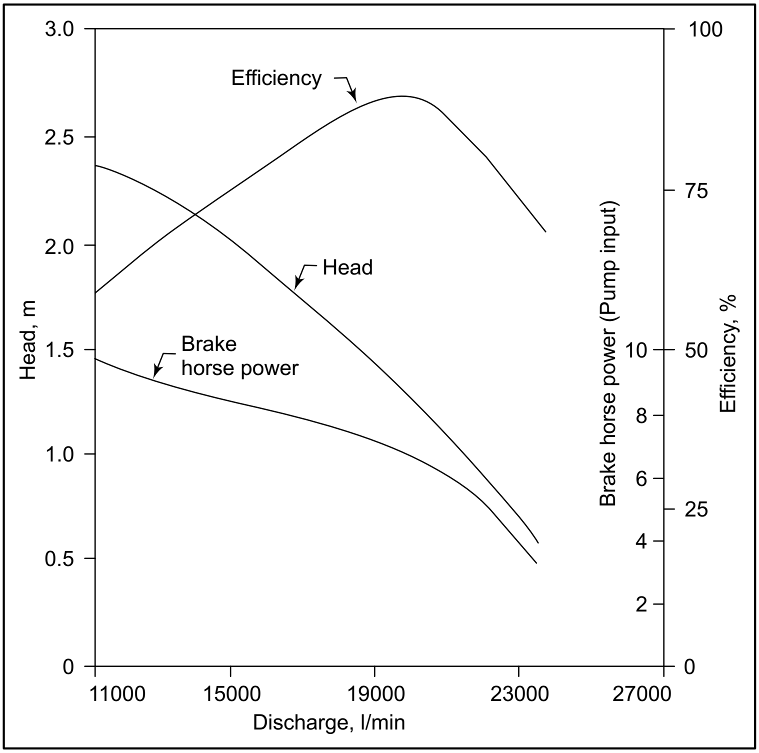

Fig. 12.6 Performance curves of a typical propeller pump

Overload is likely to occur in a propeller pump, when the discharge valve, if provided, is nearly closed. Because of the steep horse power curve at shut-off, propeller and mixed flow pumps are started against an open discharge. There is a tendency for a propeller pump to overload as the head is increased. Hence, it is essential to select a motor or engine of adequate power to operate the pump through the entire range of conditions caused by the variations in water level.

Propeller pumps are not suitable under conditions where it is necessary to throttle the discharge to secure reduced delivery. The head against which water is pumped with a propeller or mixed flow pump is an important factor influencing efficiency. Since the movement of the water is in the direction of the axis and there is a large free passage, there is very little frictional resistance to flow.

A disadvantage of the propeller pump is the high power required to operate it against a low discharge. This difficulty is eliminated in some makes of propeller pumps by providing adjustable blades. The blades are adjusted manually or automatically to suit the rate of discharge and operating head. This arrangement is advantageous where the head varies over a considerable range or where it is necessary to adjust the discharge of the pump.

12.1.4 Installation

Propeller pumps may be used as portable units (Fig. 12.7 to 12.9) or may be installed permanently (Figs. 12.10 to 12.12). When installed permanently, a propeller pump should be set on a firm foundation of adequate load bearing capacity. The entire weight of the pump is supported at the base of the floor plate. The foundation should be able to support this weight evenly on all sides of the base plate, and allow the pump to hang freely.

Fig. 12.7 A portable engine operated propeller pump lifting water from a stream to a field channel

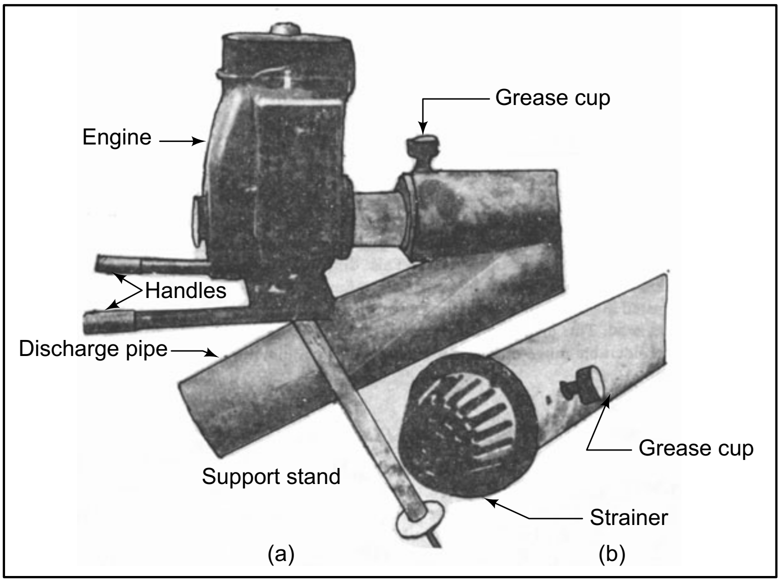

Fig. 12.8 Views of a portable engine operated propeller pump: (a) Head end, (b) Pump body and suction end

It is desirable to construct a suction bay of concrete or other masonry, and to enclose the motor and controls in a pump house. The discharge pipe should have its outlet below the minimum water level in the field channel (Fig 12.10). This would reduce the pumping head to a minimum. Installations consisting of a propeller pump combined with siphon action (Fig. 12.10) can be advantageously used for pumping water from a drainage canal, over a levee, into a river; or for pumping from a river or canal over a levee, into an irrigation system. If siphon action is availed of, the pump will have to operate only against the difference in water levels on each side of the canal bank, instead of the distance from the supply level in the canal to the top of the bank. Submerged discharges are recommended to keep pumping heads as low as possible. A non-return valve should be used at the end of the discharge pipe to prevent backflow through the pump. The propeller pump must be able to deliver a full pipe supply of water over the crest of the dike at a velocity of 1.5 m/s or more. The delivery pipe should be sufficiently submerged below the water surface in the outlet bay in order to prevent air entrainment. A siphon breaker is installed at the high point in the pipe to prevent reverse flow during power interruption. For small pumps, the non-return valve at the end of the discharge pipe may serve the purpose of the siphon breaker. An air-release valve is required to ensure smooth priming of the siphon. The valve is usually installed at the outlet of the discharge pipe and near the water surface.

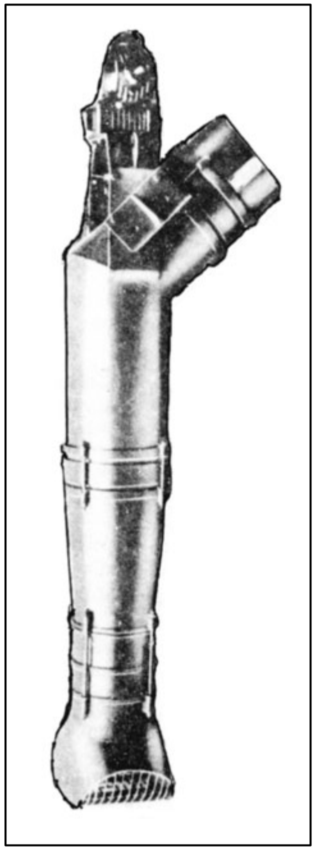

Fig. 12.9 A portable high discharge low head propeller pump, equipped with right-angle gear drive

Courtesy: Ornel Pump Co. Pvt., Ltd. Sydney

Drainage Pumps

For drainage, the propeller pump, when operated by an electric motor, is usually installed in a pump with automatic float control (Fig. 12.11). The automatic operation of the electric motor is by means of start and stop collars on a float rod. Automatic switches start and stop the pump at the required flood stages. The following are the major requirements in automatic operation of pumps:

1. The controls should be compatible with the local electric codes.
2. The controls should be well protected to prevent moisture getting into them.
3. The installation requires a greater degree of maintenance and prevention of trash getting into the sump and blocking the controls.
4. Protective controls such as overload releases must necessarily be provided.

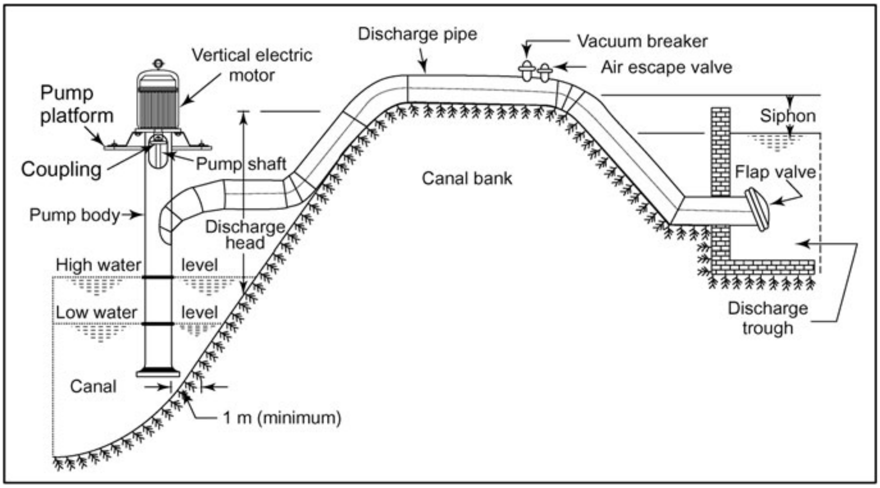

Fig. 12.10 Installation of a propeller pump to lift water from a canal/river over an embankment, taking advantage of siphon action to reduce lift. The masonry tank shown at the outlet end is optional

Number of Pumps

For large drainage installations, two or more pumps with different capacities may be necessary, one or more of them for handling the surface runoff during rainy seasons and the others for seepage or flow from tile drains. The size and number of pumps are determined mainly by the quantity of water to be pumped. When pumping from large areas and where high-value crops are involved, a large number of pumps will provide more efficient pumping over a wide range of pumping rates and also provide continued pumping even when there is a break-down in one of the pumps. The most flexible load distribution for two pumps operating in series is when the capacity of one of the pumps is about twice that of the other. In case of three pumps working together, each should be of the same capacity to obtain uniform load distribution. At least one of the pumps should be selected to operate efficiently over long periods. This is not critical in pumps designed to take care of peak discharges.

Angle-Mounted Pumps

Propeller pumps can also be angle mounted to save on installation costs (Fig. 12.12). Since the pump is set at an angle to the pump bay and water surface, it is necessary to arrange the supporting beams so that the base plate of the pump can be securely fastened. Angle-mounting eliminates the need for a supporting structure over the sump or pump bay. With an angle-mounted installation, a motor with grease-packed ball bearings is generally used.

Often, during floods, when the affected area is dewatered, it becomes difficult to install propeller pumps. Under such conditions, the pumps are installed on floating barges.

Protection Against Floating Debris

Some type of strainer or screen should be installed to exclude floating wood or other debris that would damage the propeller if drawn into the pump. Provision is made to attach a small strainer to the suction

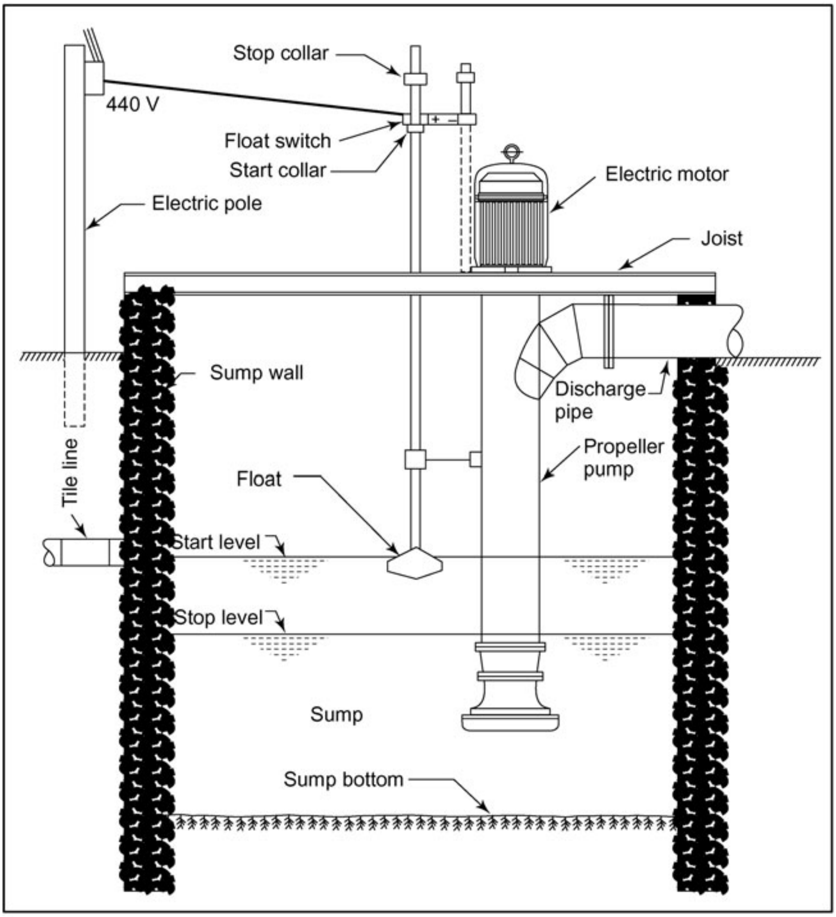

Fig. 12.11 Propeller pump with automatic switch installed in a drainage sump

bowl. An ordinary strainer is satisfactory when the water pumped is comparatively free of floating vegetation and small debris. When the source of water supply contains these foreign materials, the small strainer is apt to become clogged. Under such situations it is desirable to construct a suitable screen around the inlet of the intake bay or sump so as to increase the area for straining out small debris.

Trash Racks

Trash racks are provided to prevent the entry of trash and floating debris into sumps. The trash racks should be set at a distance not less than $2\frac{1}{2}$ times the suction bell diameter. The velocity of flow through the trash rack should not exceed 60 cm/s. Trash racks are installed in an inclined position to facilitate cleaning by hand. The following spacings of steel rods are recommended in the trash rack:

Pump diameter cm	Rod spacing cm
40	2
45-60	2.5-3.8
75-106	5

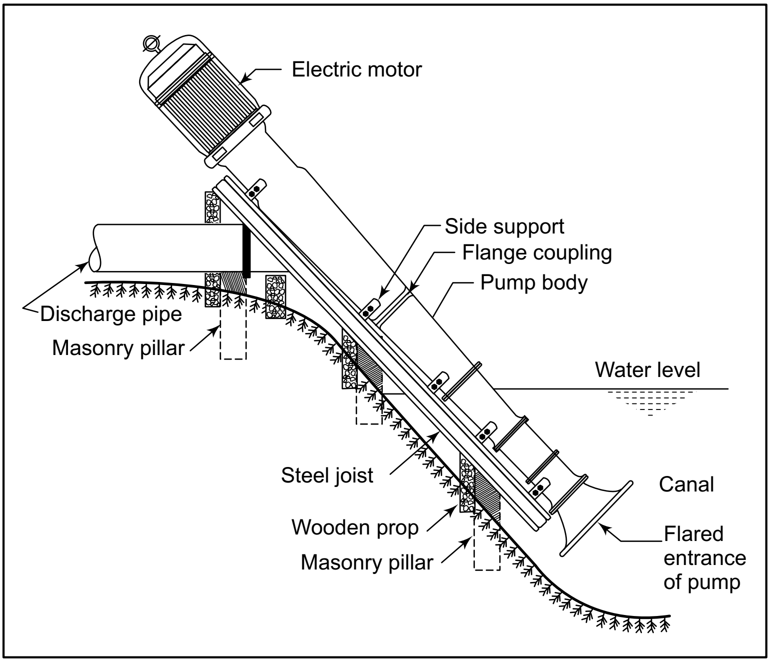

Fig. 12.12 Angle-mount installation of a propeller pump to pump water from a canal

Requirements of Submergence and Clearance

Propeller pumps are not suitable for suction lifts. The impeller bowl must be submerged with the pump operating at the proper submergence depth. The submergence depth is the distance from the pumping water level to the lowest part of the suction pipe. Table 12.1 gives the submergence usually recommended by manufacturers. Failure to keep the required submergence depth results in the absolute pressure on the propeller blade surface dropping below the vapour pressure of water. When this condition exists, vapour-filled cavities are formed and cavitation may take place. With fully developed cavitation, condensation and re-evaporation of the vapour pockets cause a series of explosions, resulting in severe mechanical vibration and rapid deterioration of the propeller blades.

TABLE 12.1 Typical Values of Submergence Clearance between Pump and Side Walls for Propeller Pump

Pump size cm	Submergence between pump and pumping water level cm	Clearance between pump and side walls cm	Clearance between suction end and sump floor cm
20	65.0	30.0	17.5
25	75.0	37.5	20.0
30	82.5	45.0	25.0
35	90.0	52.5	30.0

12.1.5 Design of Sumps for Drainage Pumps

Design considerations of sumps include the determination of their storage capacity, geometry and dimensions, and the clearances between the pump and the sides of the sump. The volume of drainage runoff to be stored in the sump may vary from a maximum of the total runoff of the design storm to a minimum, as determined by the rate of pumping that will not require a large number of starts and stops of the pump. For manual operation of the pumps, the number of starts would depend on the convenience of the operator. For automatic operation of pumps, the cycle of operation should be limited to about 10 per hour. The minimum storage capacity of the sump may be estimated as follows:

$$S = 90\,Q$$

where, S = volume of storage, m^3

Q = pump capacity, m^3/s

The dimensions of the sump may be varied to suit the field conditions and the cost of construction. The sump should not be deep but large and shallow to reduce the lift.

The sump may be constructed out of any masonry material or made of precast concrete pipes of corrugated metal. It is important that proper clearances are maintained between the end of the suction pipe and the side walls and bottom of the pit or pump intake bay. The values of clearances presented in Table 12.1 should be adhered to. Inadequate clearances can result in reduced efficiencies. When two or more pumps are installed in one pump bay, they must be separated sufficiently so as not to interfere with each other. In general, this distance should be about thrice the diameter of the suction bell of an individual pump. Slow movement of water to the pump suction and straight uniform flow are of prime importance in propeller pump performance. A restricted or unbalanced flow to the pump suction bell will usually produce a hydraulic imbalance at the impeller, resulting in vibration and excessive wear of bearings. Submergence of the propeller assembly below the water surface should be sufficient to exclude any possibility of air being drawn into the pump by vortex action.

Sumps should preferably be square since a circular shape tends to perpetuate the rotation of water in the sump, which may seriously interfere with propeller pump performance. The installation of baffle plates attached to the sides of the sump will help overcome this trouble. Tile drain inlets into the sump should be located as far away from the pump as possible to minimize the effects of turbulence and air entrainment. Each pump should have its own sump. Water supply to the sump should be arranged so that the flow goes directly to each sump rather than entering from one end, in which case the first pump would obstruct the flow to the next one.

12.1.6 Selection of Propeller Pumps

In drainage pumping installations, where the water may contain a large percentage of silt and sand during the flood seasons oil lubricated pumps are preferred. In such pumps, the shaft bearings are protected by a shaft enclosing tube, against any abrasive material in the water being pumped. In designing a drainage pumping plant, the distribution of runoff and the resulting stage of flow should be determined in order that the pumping plant is designed for maximum efficiency at the lift at which the greatest amount of pumping must be done. The maximum and minimum flood stages, with the head at the average lift at which the greatest volume pumped, must be predicted for selecting a suitable pump. For a given set of conditions, a pump may be selected using the characteristic curves of various makes of pumps. Propeller pumps are usually selected up to maximum head of 4 m. The data needed to select propeller pumps include the following:

Capacity of pump, litres/second
Discharge conditions: 1. Discharge above water level
2. Submerged discharge
3. Siphon
Static lift, metres
Length of discharge pipe, metres
Power available: 1. Electricity: voltage and phase
2. Stationary engine/tractor
Type of driver: Direct-connected, vertical hollow shaft motor, flat belt, V-belt

12.1.7 Repair and Maintenance of Propeller Pumps

Though propeller pumps are bulky, they are simple in construction. Hence, their repair and maintenance are comparatively easy. The common troubles in propeller pumps and their remedies are listed below:

1. Vibration. Vibrations may occur in a propeller pump because of poor mechanical conditions. These are usually due to worn bearings or the motor getting out of balance. However, if the entire unit vibrates, even the propeller may be out of balance. The alignment of the motor should be checked first. If the trouble is not rectified, the propeller pump will have to be removed and the bearings inspected to provide the necessary diagnosis and subsequent rectification.

2. Shaft Wear. Often, the shaft is worn out. In case it is badly worn, it will have to be replaced. Generally, wear on the shaft can be rectified by metal spraying, grinding its surface to a fine finish, and checking its straightness. When the shaft is made up of sections screwed together, the straightness will depend on the conditions of the shaft and coupling threads.

3. Oil in Water. The presence of oil in water indicates that water backs up into the oiler because of the wearing rings at the top of the propeller. The wearing rings should be inspected and replaced if necessary.

4. Bearing Wear. Wearing of the bearings may take place because of various reasons. In case of metal bearings, the wear can be checked with micrometres. The bearing will have to be replaced if the wear is more than permissible. In case of rubber bearings, the bond between the rubber and metal backing is often lost. Under such conditions, the bearings should be replaced.

5. Imbalanced Propeller Blades. An imbalance is caused in the propeller because of bent or damaged propeller blades. The damaged blades will have to be replaced or repaired, depending upon the extent of damage.

6. Pitting and Erosion. Pitting of the suction bell near the leading edges of the propeller blades may be caused by the abrasive action of solids in the pumped liquid. Pitted areas can be repaired by metal spray, ensuring the desired finish.

7. Wearing Rings. In case a propeller pump has a wearing ring on its hub, the clearance between this ring and the stationary casing ring should be checked. The wearing rings will have to be replaced if the clearance is more than 0.025 cm.

12.2 MIXED FLOW PUMPS

A mixed flow pump (Fig. 12.13) combines some of the features of both the vertical turbine pump and the propeller pump (Fig. 12.1). It is applicable for high discharge medium head conditions. The head usually varies from 3 to 10 metres. Mixed flow pumps are extensively used for drainage pumping and in pumping from canals, rivers, or streams. They are also popular in lift canal projects.

Mixed flow pumps have medium specific speeds. The specific speed varies from to 90 to 160. Francis-type impellers fall in the specific speed range of 30 to 90.

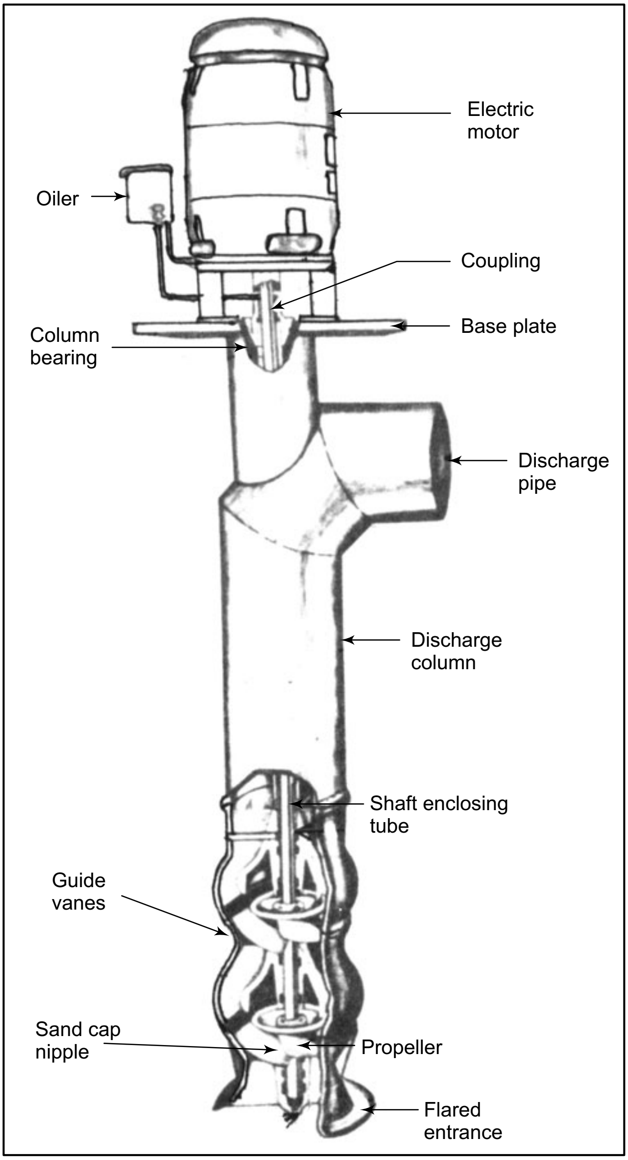

Fig. 12.13 View of a two-stage mixed flow pump with the pump element exposed

12.2.1 Principle of Operation and Construction

The characteristic difference in the principle of operation of the pumping element of mixed flow pumps, as compared to vertical turbine pumps and propeller pumps, is shown in Fig. 12.1. In a mixed flow pump, the head is developed partly by centrifugal force and partly by the lift of the vanes on the liquid. This type of pump always has a single-inlet impeller. The flow enters axially and discharges in an axial and radial direction. Hence the name mixed flow pump.

Mixed flow pumps may be oil lubricated or water-lubricated. The construction of a mixed flow pump is similar to that of the propeller pump (Figs. 12.13 and 12.14). The main difference between the two is in the construction of the impeller. The impeller blades of mixed flow pumps are designed to give an outward thrust to the water, in addition to imparting to it an upward velocity. Common types of impellers of mixed flow pumps are shown in Fig. 12.15. The diffuser provided above the impeller guides the water to the column and straightens the flow. The suction bell is of the circular type, with a flared approach for smooth entrance into the impeller.

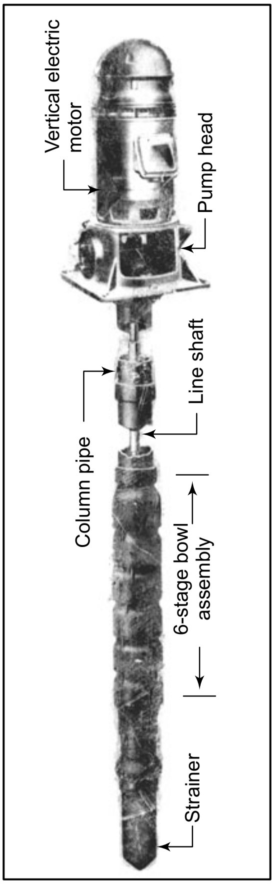

Fig. 12.14 Partially exposed view of a vertical multi-stage mixed flow pump
Courtesy: Lee, Howl & Co. Ltd., London

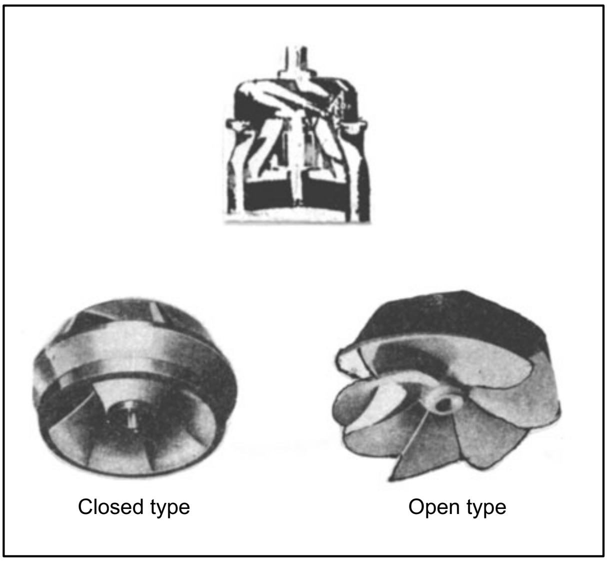

Fig. 12.15 Impellers of mixed flow pumps
Courtesy: Lee, Howl & Co. Ltd., London; Ebara Manufacturing Co. Pvt. Ltd., Tokyo

The bottom bearing is grease-packed with a sand cap to prevent the entrance of abrasive particles. The details of construction of the column assembly and pump drive are similar to those of the propeller pump.

12.2.2 Operating Characteristics and Installation

Typical characteristic curves of a mixed flow pump are presented in Fig. 12.16. The head-capacity curve of a mixed flow pump is usually steeper than that of a centrifugal pump, but not as steep as that of a propeller pump. Unlike the propeller pump whose horse power curve slopes sharply down to the right, the horse power curve of a mixed flow pump has almost a constant value from the shut-off point to just before attaining the 'wide open' position. This feature is important in pumping high discharges with motor driven pumps, in cases where the operating heads vary widely. In such a situation, minimum changes in pump capacity are possible through a wide variation in head, without danger of overloading the motor.

The installation of a mixed flow pump is similar to that of a propeller pump. The requirements of sump and clearance between the pump and sump walls and floor are the same as specified for propeller pumps.

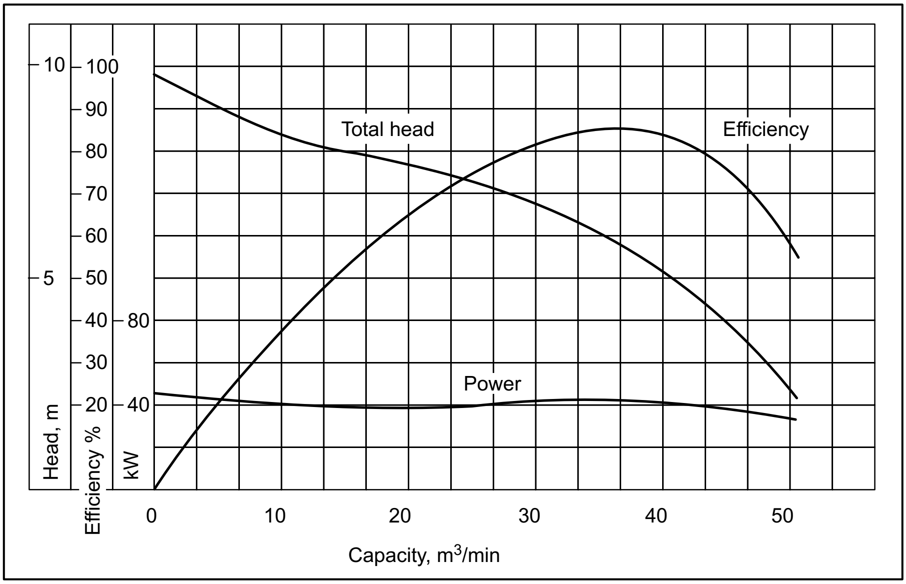

Fig. 12.16 Typical performance curves of a mixed flow pump
Courtesy: Ebara Manufacturing Company Ltd., Tokyo

12.2.3 Selection of Mixed Flow Pumps

Mixed flow pumps are either water lubricated or oil lubricated. In case of disposal of drainage runoff where the water may contain large quantities of silt and sand, oil lubricated pumps are preferred. However, for irrigation water lifting schemes, water lubricated mixed flow pumps are more economical.

In selecting a pump, the desired ranges of head and discharge are estimated. The pump is selected on the basis of the characteristics of various pumps, so as to obtain the maximum efficiency. The data needed to select a mixed flow pump are similar to those specified for a propeller pump. Mixed flow pumps are usually adopted for a range of heads between that specified for propeller pumps and centrifugal pumps. Thus, these pumps may be adopted for heads varying from 3 to 10 m and requiring large capacity. The pumps may be single stage (for low head) or multistage (for larger head).

12.3 JET PUMPS

Jet pumps, also called ejector pumps, are usually used in water supply schemes to pump small-to-medium quantities of water at high suction lifts. In a centrifugal-jet pump combination (Fig. 12.17), the centrifugal pump is mounted close to the electric motor or engine, located at the ground surface, and furnishes the driving head and capacity for the jet unit placed in the well below the water surface. For shallow wells upto 7.5 m, the jet mechanism can be placed on the ground surface (Fig. 12.18) or built into the centrifugal pump casing. The advantage of the centrifugal pump-jet assembly is that there are no moving parts in the well and the pump-prime mover assembly can be located at a convenient point at the ground surface.

12.3.1 Construction and Operation

Jet pumps consist of a combination of a centrifugal pump and a jet mechanism or ejector. The principal parts of the jet mechanism are a nozzle and a venturi (Fig. 12.19). At the pump delivery, a portion of the high-pressure water returns through the pressure pipe to activate the nozzle in the ejector. The nozzle is so shaped as to reduce smoothly but abruptly the area through which the flow must pass, thus increasing the velocity of flow. This creates a low-pressure area around the venturi, which draws more water from the wall. The gradual enlargement in the venturi tube to the full diameter of the suction pipe reduces the velocity of water with a minimum of turbulence. The vacuum created by the impeller of the pump, placed at the ground surface, draws the flow through the suction pipe. The water is pumped out through the delivery pipe at the desired pressure. The additional supply of water obtained from the well is discharged past a control valve (Fig. 12.18), while the volume required for producing flow is recirculated through the pressure pipe. The control valve is set to maintain the necessary pressure to produce flow at the existing pumping head.

Both horizontal and vertical centrifugal pumps are adapted to operate conjunctively with the ejector mechanism. Diffuser-type centrifugal pumps are commonly used in jet pumps especially when used with automatic water supply systems. Figure 12.17 shows the view of a typical centrifugal pump based jet pump.

The following are the major features of jet pumps which make them suitable for domestic water-supply systems:

1. The pump can be kept offset from the well, in a clean, dry and convenient place with easy accessibility.
2. The moving part is limited to the pump impeller, thus minimizing the cost of maintenance of the unit.
3. When equipped with a pressure control valve, the pump provides a smooth non-pulsating flow.

4. Water hammering or knocks, which are common in power-operated reciprocating pumps used in water supply systems, are eliminated.
5. The pump is easily adapted to automatic water supply systems by providing a pressure tank and control valves.
6. When provided with pressure control, the power required for pumping is constant at all points of operation.

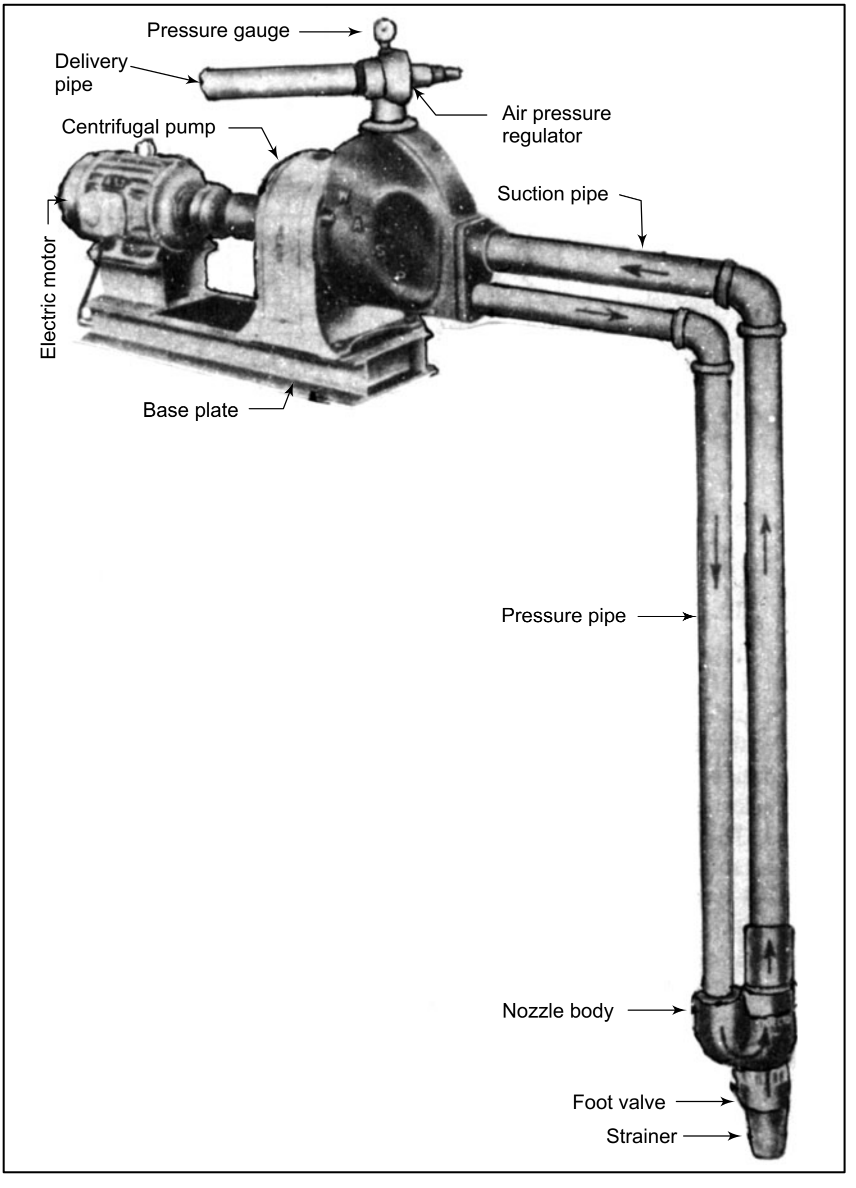

Fig. 12.17 A centrifugal-jet pump assembly coupled to an electric motor
Courtesy: Water Supply Specialists Pvt. Ltd., Mumbai (Anon., 1982b)

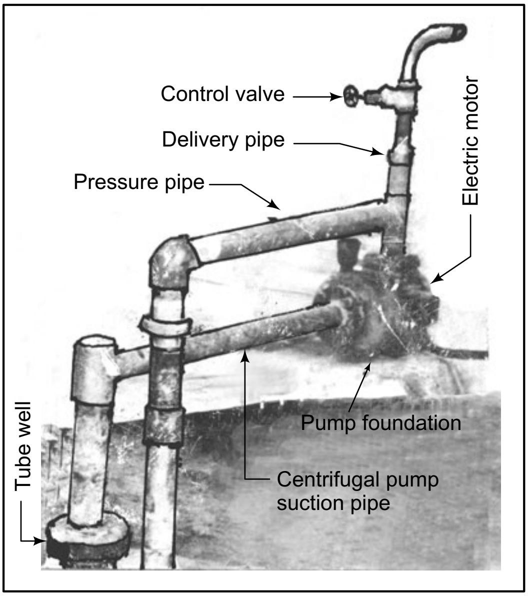

Fig. 12.18 A centrifugal-jet pump installed in a shallow tube well

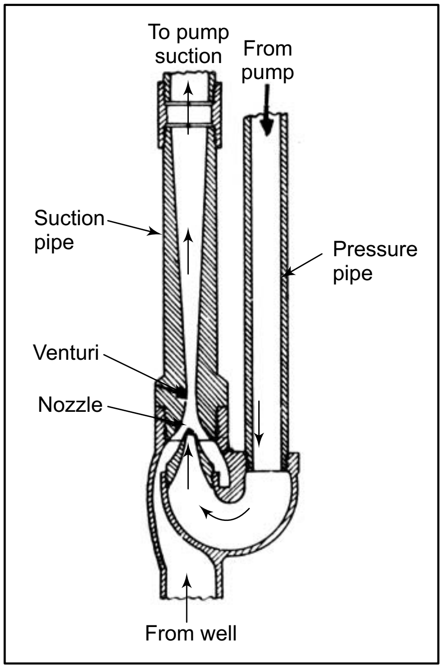

Fig. 12.19 Sectional view of a twin-type jet assembly

Jet pumps, however, have limited application in pumping for irrigation, due to the higher cost of the pumping set, as compared to the conventional centrifugal pump, and the low efficiency of the unit. The highest efficiency usually obtained from jet pumps is about 35 per cent, as compared to 70 to 85 per cent obtained from a properly selected centrifugal pump. Further, jet pumps are not easily adapted to locations where the water levels are subject to large seasonal fluctuations, or where severe corrosion or incrustation may cause enlargement or blocking of jet nozzles.

12.3.2 Types of Jet Pumps

Jet pumps can be broadly grouped into (1) *shallow well jet pumps,* and (2) *deep well jet pumps*. In a shallow well jet pump, also called an ejecto pump, the ejector assembly is located inside the pump body and not inside the well as is the usual case. The advantage of the ejector assembly is to increase the suction lift. As compared to a volute centrifugal pump which has a maximum suction lift of about 6.5 m, the suction lift of a shallow well ejecto pump is about 8.5 m. It is also suitable for automatic water supply systems.

In deep well ejecto pumps, the ejector assembly is located inside the well. It can lift water from depths upto about 50 m. Special type deep well ejecto pumps can be applied to lift water upto about 90 m.

Based on the construction features and adaptability to the size and yield of tube wells, jet pumps can be classified into (1) twin-type ejecto pumps, (2) packer-type ejecto pumps, and (3) duplex-type ejecto pumps.

Twin-Type Ejecto Pumps

In case of a twin-type ejecto pump, there are two pipes, namely the pressure pipe and the delivery pipe, leading to the suction side of the centrifugal pump. Pressurized water flow through the pressure pipe to the nozzle. Water sucked through the foot valve and that passing through the nozzle get mixed and then flow through the pump suction pipe, often referred to as the delivery pipe, into the pump. Twin-type ejector assemblies are used in open wells and in tube wells having no casing pipe (as in the case of bores of fissured formations) or when the casing is slotted at levels above the location of the ejector assembly.

Packer-Type Ejecto Pumps

In case of a packer-type ejecto pump (Fig. 12.20), the casing of the tube well functions as the pressure pipe. Figure 12.21 shows details of the ejector assembly of a packer-type pump. A special adapter is used to connect the pump with the well casing. Pressurised water flows through the tube well casing and enters the nozzle. Thus, one pipe is eliminated, which results in a substantial economy. However, a packer-type ejecto pump requires a bore which is cased throughout, preferably with seamless pipes. The pump is suitable for use in tube wells as small as 5 cm in diameter. It is suitable for much higher discharge when used in small diameter wells, as compared to twin-type ejecto pumps.

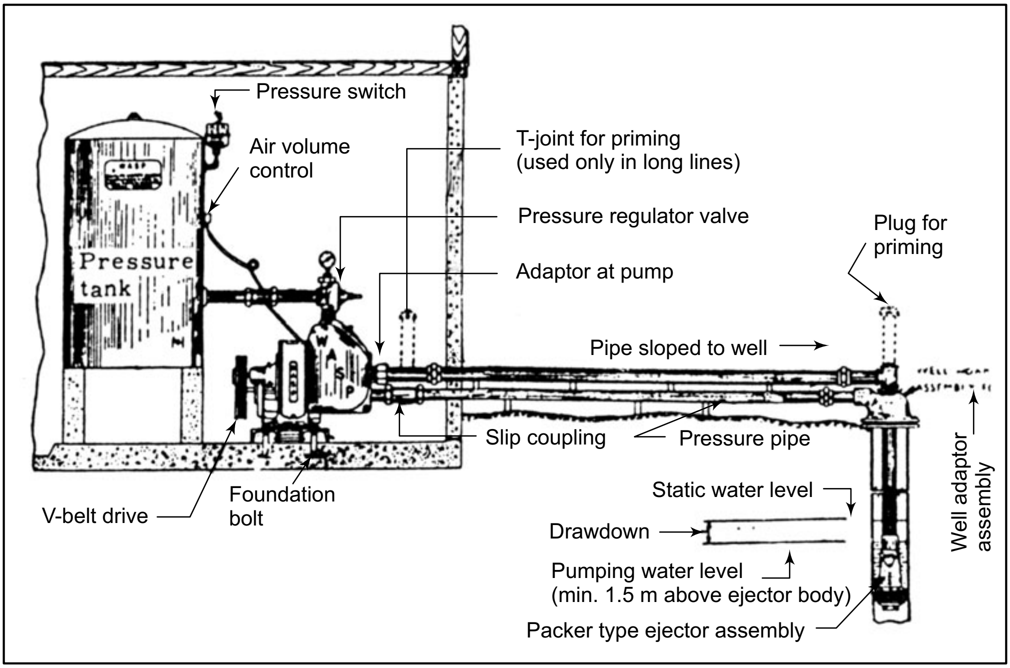

Fig. 12.20 Details of installation of jet pump equipped with packer-type ejector assembly and pressure tank in a shallow tube well

Adapted from: Water Supply Specialists Pvt. Ltd., Mumbai (Anon., 1982d)

Duplex-Type Ejecto Pumps

Basically, the duplex-type ejector assembly is similar to the packer-type assembly. However, the cup leather is eliminated and in its place a threaded metallic duplex adapter (Fig. 12.22) is used. A separate pressure pipe (outer pipe) is fixed to the adapter. The diameter of the outer pipe is smaller than the well bore. Thus, there are two concentric pipes in the bore. The inner delivery pipe is the same as in packer-type ejectors. Duplex-type ejecto pumps are suitable for wells which have bores which are not fully lined with casing pipes. Minor variations in the bore size or non-uniformities in the casing pipe will not influence the performance of the pump. It also eliminates the use of costly seamless pipes for well casing.

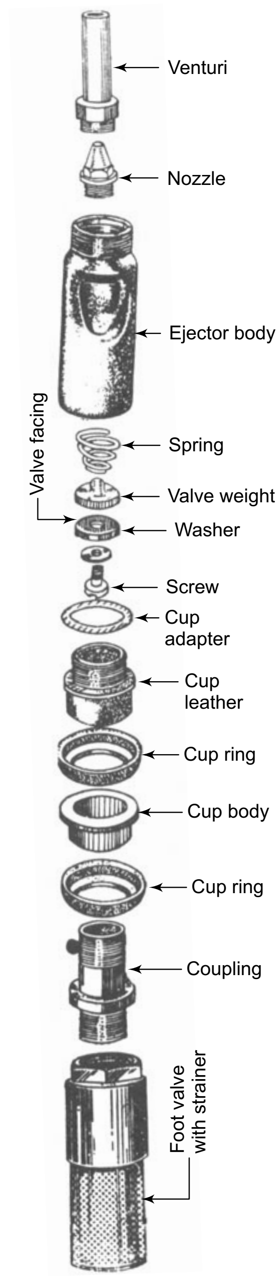

Fig. 12.21 Exploded view of packer-type ejector assembly
Courtesy: Water Supply Specialist Pvt. Ltd., Mumbai (Anon., 1982c)

Performance Characteristics

An important factor governing the capacity and efficiency of a jet pump is the selection of the jet to correspond to both the type of pump and the depth of water level in the well. The efficiency of the pump is influenced mainly by the nozzle-throat ratio. For small jet pumps used in connection with domestic water supply the spacing between the nozzle and the throat is equal to one nozzle diameter. The length of the throat is about six throat diameters. The characteristic curves of a typical jet pump at different values of the driving heads are shown in Fig. 12.23. These characteristics can be described by the following three ratios (Gosline and O'Brien, 1934):

Area ratio, $$R = \frac{A_1}{A_2} = \frac{\text{Nozzle area}}{\text{Throat area}} \quad (12.1)$$

Capacity ratio, $$M = \frac{Q_2}{Q_1} = \frac{\text{Pumped capacity}}{\text{Driving capacity}} \quad (12.2)$$

Head ratio,
$$N = \frac{H_d - H_s}{H_1 - H_d} = \frac{\text{Net jet pump head}}{\text{Net driving head}} \quad (12.3)$$

The driving capacity Q_1 and the driving head H_1 are furnished from the centrifugal pump unit. The capacity Q_2 under the head H_s enters the jet pump suction from the well. Hence, the capacity of the jet pump Q is the sum of Q_1 and Q_2,

$$Q = Q_1 + Q_2 \quad (12.4)$$

The efficiency of the jet pump e_j is defined as

$$e_j = \frac{Q_2 (H_d - H_s)}{Q_1 (H_1 - H_d)} = MN \quad (12.5)$$

where, H_1 = head on the jet pump nozzle (driving head furnished by the centrifugal pump), m
H_d = discharge head of the jet pump, m
H_s = suction head (the head at which water enters the jet pump suction from the well), m

The efficiency of a jet pump depends upon the value of MN, i.e., a higher value results in a greater efficiency. These values are governed by the nozzle-throat ratio, which is the most important design element for jet pumps. The highest efficiency (about 35%) of jet pumps has been obtained for $R = 0.28$ (Stepanoff, 1992).

The maximum capacity possible for a given suction head is limited by *cavitation*, which acts in the same manner as in centrifugal pumps, irrespective of the reduction of the discharge head. The maximum suction flow is given by:

$$Q_2 = (A_2 - A_1)\sqrt{2g\,(H_s - h_s)} \quad (12.6)$$

where, h_s represents the head losses in the suction pipe. Cavitation results in pitting of the throat walls and is accompanied by the typical cavitation noise.

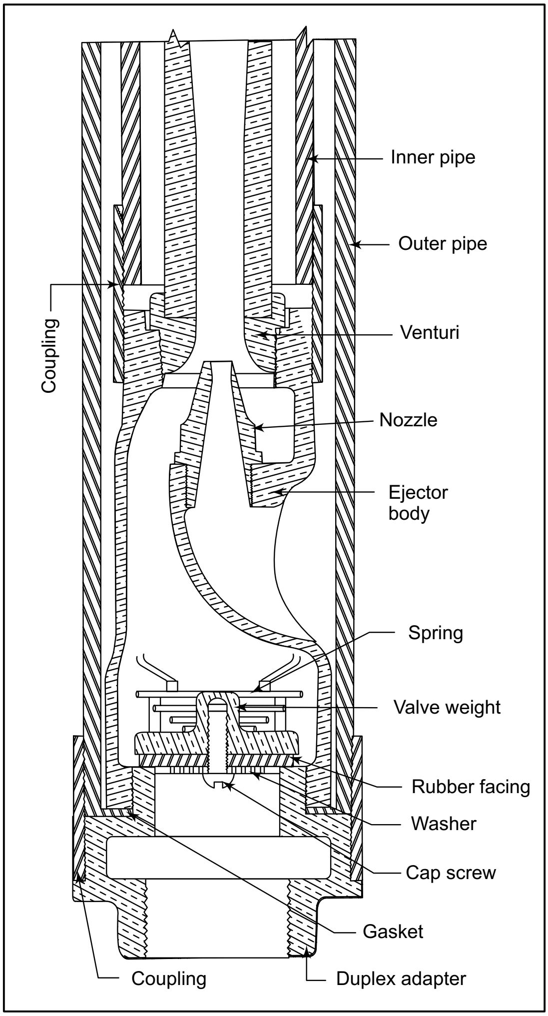

Fig. 12.22 Sectional view of duplex-type ejector assembly

Courtesy: Water Supply Specialists Pvt. Ltd., Mumbai (Anon., 1982c)

12.3.3 Design of Jet Pumps

The design of a jet pump includes the determination of driving capacity Q_1 for a given driving head H_1, the jet pump head H_d, and the suction head H_s, which are fixed by site conditions. The design also involves determination of the size of the throat and nozzle.

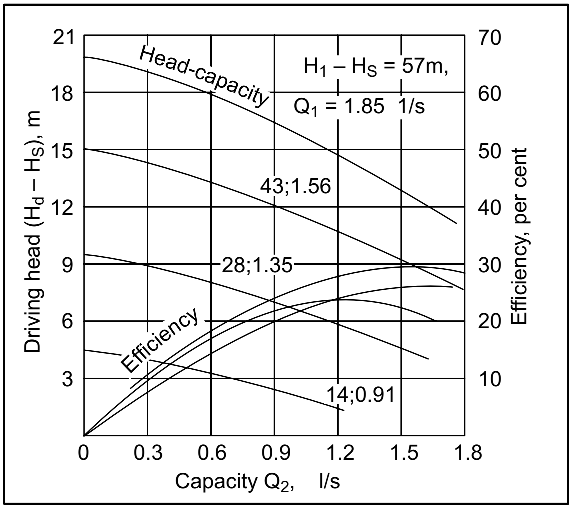

Fig. 12.23 Performance characteristics of jet pump under varying driving heads for specific head-capacity curves

Adapted from: Gosline and O'Brien (1934)

The step-by-step procedure for the design of jet pumps is as follows:

1. The value of N is given by Eq. (12.3),

$$N = \frac{H_d - H_s}{H_1 - H_d} = \frac{\text{Net Jet pump head}}{\text{Net driving head}}$$

2. The value of M for an assumed efficiency and known value of N can be determined from Eq. (12.5),

$$MN = e_j$$

3. The value of R is determined from the relation

$$1 + M = 1/\sqrt{R}$$

4. The value of Q_1 is determined for known values of Q_2 and M

$$Q_1 = Q_2/M$$

5. The nozzle size is obtained using the relationship

$$Q_1 = CA_1 \sqrt{2g\,H_1} \qquad (12.7)$$

where, A_1 is the area of the nozzle and C is the nozzle discharge coefficient. The value of C is usually assumed to be 0.95.

6. The throat area A_2 is determined from the relationship

$$A_2 = A_1/R$$

Example 12.1 Design a jet pump for a driving head of 15 m, and a jet pump head of 5 m. The suction head H_s may be assumed to be zero. The estimated efficiency of the pump is 30 per cent. The combined discharge Q, $(Q_1 + Q_2)$ is 0.01 m^3/s.

Solution

1. The value of $N = \dfrac{H_d - H_s}{H_1 - H_d} = \dfrac{5-0}{15-5} = 0.5$

2. The value of M is determined from the relationship $MN = e_j$

$\therefore \quad M \times 0.5 = 0.30$

Hence, $\quad M = \dfrac{0.30}{0.50} = 0.6$

3. The value of R is determined from the relationship

$$1 + M = \frac{1}{\sqrt{R}}$$

$$\therefore \quad \sqrt{R} = \frac{1}{1+M} = \frac{1}{1+0.6} = 0.625$$

$$\therefore \quad R = 0.39$$

4. The nozzle size A_1 is obtained from the relationship

$$Q_1 = CA_1 \sqrt{2g\,H_1}$$

or

$$A_1 = \frac{Q_1}{C\sqrt{2g\,H_1}}$$

$$Q_1 = Q_2/M = (Q - Q_1)/M$$

$$MQ_1 = Q - Q_1$$

$$\therefore \quad Q_1 = \frac{Q}{(M+1)}$$

$$= \frac{0.01}{0.6+1} = 0.00625 \text{ m}^3\text{/s}$$

$$A_1 = \frac{0.00625}{0.95\sqrt{2 \times 9.81 \times 15}} = 0.00038 \text{ m}^2$$

$$= 3.8 \text{ cm}^2$$

$$\therefore \quad \text{Diameter of nozzle} = \sqrt{\frac{3.8 \times 4}{\pi}} = 2.20 \text{ cm}$$

5. The throat area A_2 is given by

$$A_2 = A_1/R = \frac{3.8}{0.39} = 9.74 \text{ cm}^2$$

$$\therefore \quad \text{Diameter of throat} = \sqrt{\frac{9.74 \times 4}{\pi}} = 3.52 \text{ cm}$$

12.3.4 Selection of Jet Pumps

The selection procedure for jet pumps in combination with centrifugal pumps is similar to that for centrifugal pumps (Sec. 9.8). For given discharge capacity, total head and operating conditions, the desired pump combination is selected from the performance graphs/tables supplied by the manufacturers. The specifications should conform to the standards prescribed by an authorised agency like the Bureau of Indian Standers. A major factor in the total head of a jet pump is the friction in the pipeline under situations where the pump is located away from the well. The capacity of the pump is determined on the basis of the per capita requirement of the population served by the pump, or the yield of the well, whichever is applicable.

EXAMPLE 12.2 A jet pump is to be installed in a 10 cm shallow tube well. The required discharge capacity is 35 1/min. The total suction head is 10 m. Select a suitable jet-type centrifugal pump, and diameters of the suction pipe, pressure pipe and the discharge pipe, using the performance data presented in Table 12.2 (supplied by a standard manufacturer).

Solution
Referring to Table 12.2, for a suction head of 10 m, jet model JM_3 and a 2-stage centrifugal pump model CP_3 of size 30 mm x 30 mm, will give a discharge of 36 1/min, which will satisfy the requirement. The recommended diameters of the suction pipe and pressure pipe are 30 mm and 25 mm, respectively (Table 12.2). The recommended diameter of the discharge pipe is 25 mm. An electric motor of 2 bhp would be required.

12.3.5 Installation

General procedures in the installation of centrifugal pumps apply to jet pumps as well. The following are the special requirements in the installation of jet pumps:

1. Only galvanized pipes or rigid PVC pipes are used as pump accessories in water supply schemes. For pressure water supply systems, air-tight connections are of added importance.
2. The pump is installed in a clean, dry location. Sufficient space is provided for ventilation of the electric motor.
3. The pump and pressure tank are raised slightly to permit air circulation under the tank and to retard corrosion.
4. When single-phase capacitor-type motors are used to operate the pump, they should be equipped with iron-clad switches with fuses. Three-phase motors are protected by starters equipped with over-load-protection devices.
5. A shut-off valve is usually recommended between the pump and the pressure tank. This will help retain the water and air in the tank when the pump is to be disconnected for servicing and repairs.
6. The piping from tank to pump should be level or sloping to the pump. This will facilitate the discharge of air into the tank. Similarly, the piping between the pump and the well should slope to the well.
7. T-joints with risers and plugs are usually installed at the well and at the pump.
8. Avoid starting the motor without having water in the pump casing, since it may damage the rotary seal, causing leakage.

TABLE 12.2 Performance of Jet Pumps Considered for Selection in Example 12.2

Item no.	Jet model	Pump model	RPM	Total head m	Motor bhp	Capacities in 1/min based on submergence of 1.5 m in water for the jet and assuming that the pump offset from the well is not more than 1.5 m when running at 1425 rpm. Suction head, m				Minimum inside dia. of tube well or open well, cm	High suction jet		Size of dis-charge pipe, mm
						10	12	15	20		Suction pipe dia., mm	Pressure Pipe dia., mm	
1	JM_1	CP_1 2-stage 30 mm × 30 mm	1425	30	1 hp	25	20	15	12.5	7.5	25	20	20
2	JM_2	CP_2 2-stage 30 mm × 30 mm	1425	25	1 hp	30	27			10.0	30	25	25
3	JM_3	CP_3 2-stage 30 mm × 30 mm	1425	30	2 hp	36	33	30	27	10.0	30	25	25
4	JM_4	CP_4 2-stage 40 mm × 40 mm	1425	25	2 hp	60	50	45		12.5	40	30	30
5	JM_5	CP_5 2-stage 40 mm × 40 mm	1425	30	5 hp	100	75	70	62	15.0	50	40	40

12.3.6 Pump Troubles and Remedies

Table 12.3 summarises the common jet pump troubles and their causes and remedies.

TABLE 12.3 Possible Troubles of Jet Pumps and Their Causes and Remedies

Trouble	Possible causes	Suggested remedy
Pump not delivering Water	(a) Leaky suction pipe	(a) Make sure all pipe connections are pressure-tight.
	(b) Inadequate priming	(b) Do proper priming by adding water.
	(c) Injector nozzle clogged	(c) Remove the injector and clean nozzle of any obstruction. Make sure piping is absolutely clean before replacing injector.
	(d) Foot valve stuck or strainer clogged	(d) Remove, repair and clean.
	(e) Water level below foot valve	(e) Lower injector or foot valve deeper in the well.
	(f) Horizontal piping does not slope up from well to pump	(f) Make sure there is no air trap in the horizontal piping between the well and the pump.
	(g) Pump rotating in wrong direction	(g) Check electric connections of the motor.
Low pump capacity	(a) Water level too low	(a) Check water level against performance tables to make sure that it is not out of range of pump or injector used.
	(b) Low well capacity	(b) This will result in excesive draw-down in the well. Usually corrected by lowering Jet further in well.
	(c) Injector nozzle clogged	(c) Remove injector from well and clean nozzle in case of any obstruction. Make sure pipes are clean before replacing.
	(d) Foot valve stuck or clogged	(d) Remove injector from well and clean strainer. Make sure foot valve is not stuck.
	(e) Leaky suction pipe	(e) Make sure all pipe joints are pressure-tight so that no air can leak under suction.
	(f) Worn or defective pump parts or plugged impeller	(f) Replace worn out parts. Clean parts if required.
Pumps starts and stops frequently	(a) Leak in pumping system	(a) Check all valves and make sure there is no leakage in system.
	(b) Foot valve may be leaking	(b) Remove foot valve and repair it.
	(c) Improper connection of service pipes	(c) In case of domestic water supply, on installation where pump is installed at some distance from point of water usage, service line should be connected to water storage tank rather than to pump or on the pipe-line from pump to tank.
Pump loses prime	(a) Water level falls below foot valve	(a) Check water level and lower foot valve or jet, if possible.
	(b) Air leaks in suction line	(b) Look for possible air leaks in suction line and, if observed, correct leaks. On high suction lifts, it is important to prevent any leaks in suction line.
Pump will not shut off	(a) Injector nozzle clogged	(a) Remove injector and clean with stiff wire.
	(b) Pump may have lost prime	(b) See instructions given above.
	(c) Water level may be too low in well	(c) Check water level against performance chart of pump to make sure that the correct jet is being used on deep well pumps, or that water level is not too low for shallow well pumps.

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SHORT QUESTIONS

I. State True (T) False (F).

1. Jet pumps are adapted to situations of high suction head and low discharge.
2. In Jet pumps the prime mover is located in the well.
3. Propeller pump has high efficiency under low heads.
4. In propeller pump the bowl assembly is submerged under water.
5. There are no shaft enclosing tubes in oil lubricated propeller pump.
6. The head-capacity curve of a propeller pump is flatter than that of a centrifugal pump.
7. The frictional resistance to flow in the propeller pump is more than the centrifugal pump.
8. In some makes of a propeller pump the blades can be adjusted to suit the rate of discharge and operating head.
9. In propeller pumps, a siphon breaker installed in the pipe helps to prevent reverse flow during power interruption.
10. Propeller pumps are suitable for suction lifts.
11. In propeller pumps, failure to keep the required submergence results in cavitation.
12. Mixed flow pumps are extensively used for pumping ground water.
13. In mixed flow pump, the head is developed partly by centrifugal force and partly by the lift of the vanes on the liquid.
14. The head-capacity curve of a mixed flow pump is usually steeper than that of a propeller pump.
15. The mixed flow pump is more efficient than propeller pump under variable operating head.
16. The discharge versus horse power curve of a mixed flow pump has almost a constant value.
17. Mixed flow pumps may be single stage or multistage.
18. Jet pumps are used to pump small amount of water at low suction lifts.
19. Jet pumps are also called ejecto pumps.
20. In shallow well ejecto-pumps the ejector assembly is located inside the well.
21. For small-jet pumps, the spacing between the nozzle and the throat is equal to one nozzle diameter.
22. Nozzle-throat ratio is the most important design element for jet pumps.

Ans. True : 1, 3, 4, 8, 9, 11, 13, 15, 16, 17, 19, 21, 22.

II. Select the correct answer.

1. The pump most suitable for delivering large quantities of water under low head is
   (a) submersible pump (b) centrifugal pump
   (c) propeller pump (d) turbine pump
2. Propeller pumps are
   (a) axial flow pumps (b) mixed flow pumps
   (c) radial flow pumps (d) volute pumps
3. The number of blades in propeller pumps is
   (a) less than 3 (b) between 3-6
   (c) between 6-9 (d) more than 9
4. Propeller pumps are usually selected upto a maximum head of
   (a) 2 m (b) 4 m
   (c) 6 m (d) 8 m

5. In mixed flow pumps the flow
   (a) enters and discharges axially
   (b) enters and discharges radially
   (c) enters axially and discharges in an axial and radial direction
   (d) enters radially and discharges in an axial and radial direction
6. The highest efficiency usually obtained from jet pump is about
   (a) 35 per cent (b) 45 per cent
   (c) 55 per cent (d) 65 per cent
7. The length of throat in an efficient jet pump is about
   (a) two throat diameters (b) four throat diameters
   (c) six throat diameters (d) eight throat diameters
8. The head-capacity curve is steepest in
   (a) centrifugal pump (b) submersible pump
   (c) mixed flow pump (d) propeller pump
9. The most suitable pump under conditions requiring throttling of discharge is
   (a) centrifugal pump (b) rotary pump
   (c) propeller pump (d) reciprocating pump
10. The most suitable pump under conditions of large seasonal fluctuations in water level is
   (a) jet pump (b) propeller pump
   (c) centrifugal pump (d) submersible pump

Ans. 1. (c) 2. (a) 3. (b) 4. (b) 5. (c) 6. (a) 7. (c) 8. (d) 9. (a) 10. (d)

13

Application of Non-Conventional Energy Sources in Pumping

Energy sources may be classified broadly into two groups, commercial and non-commercial. Commercial energy sources are coal, petroleum oil (petrol/diesel), petroleum gas, electricity (hydro- and thermal) and nuclear fuel. They account for about 46 per cent of the total primary energy supply in India. The balance 54 per cent of the energy supply is from non-commercial sources which comprise mainly firewood and agricultural and animal wastes.

Fossil fuels (petrol/diesel) and electricity generated at centralised grid power systems have been the conventional energy sources in pumping for irrigation and water supply. In spite of their outstanding merits, fossil fuels have some major limitations. First, they are non-renewable and their supply is bound to reduce and approach exhaustion with continued exploitation. The cost of diesel and their distribution to remote areas may often become prohibitive in many countries. Further, their indiscriminate use results in environmental hazards like atmospheric pollution. Likewise, the cost of generating electricity at hydro-electric and thermal stations, transmitting it over long distances and distributing it to individual small land holdings for operating pumps is becoming increasingly high. Nuclear fuel is used only to a very small extent. It is also non-renewable and prone to create environmental hazards, unless exploited with great care. Demands for electrical power often exceed the available supply. Efforts are, therefore, being made to adopt alternative energy sources in pumping, wherever feasible.

The four major alternative energy sources which have established their feasibility in water pumping are wind, micro hydro-power, sun and biomass. All these energy sources are renewable and are available to the farmer or the community at little or no cost. They are also free from environmental hazards.

Water lifting devices using alternative energy sources are windmill pumps, hydraulic rams, mini-turbines, solar pumps and biogas/producer-gas run engine-pumping sets. While the windmill is an invention that dates back to the earliest times of recorded history, the hydraulic ram was developed towards the end of the eighteenth century. Indigenous water turbines have been in use for the past several centuries for operating saw mills and flour mills. The use of solar energy, biogas and producer gas in pumping have essentially been developments of the later part of the twentieth century. All these devices are suitable mainly in small-scale pumping. Their feasibility would depend on the extent of avilability of the energy source (wind/stream flow/sun/biomass) during the year, with reference to irrigating seasons, the relative cost of development and utilization of the energy source, size of land holdings, population to be served and the depth to water table.

13.1 WINDMILLS

Windmill utilizes the kinetic energy associated with the movement of atmospheric air. Wind is a free source of energy that can be easily and effectively utilized for lifting water in areas where winds of sufficient velocity can be relied upon. Wind conditions, source of water, and the technology and capital available are the major factors influencing the practical use of wind energy efficiently, on a large scale.

13.1.1 Scope and Feasibility in Water Lifting

Windmill is a useful source of mechanical power in many developing countries. It is one of the earliest inventions in irrigated agriculture. There is evidence that the ancient Egyptians used windmills, as early as 3600 BC, to lift water to irrigate their fields and grind grain. The Persians were known to grind grain through vertical-axis sail-type windmills. Windmills were in use in China since the tenth century, for irrigating small fields. In Thailand, simple windmills constructed locally, using wooden or bamboo poles and cloth sails, have been in use for several centuries to lift water through water ladders. Windmills were introduced in Europe in the twelfth century. They were very popular in Holland and Denmark, especially for drainage pumping. Nearly 30,000 windmills, capable of producing a total of 100,000 kilowatts of power, were reported to be operating in Denmark at the beginning of the twentieth century. In Holland, about 9000 windmills were working in the year 1850, mainly for drainage pumping. Some of them had a power output as high as 50 hp. With the major advance in rural electrification and the increase in size of farm holdings in the more developed countries of Europe and North America, the use of windmills became less popular for irrigation and drainage.

The seasonal nature of winds, the low energy output of windmills and the high cost of commercially produced mills are considered major limitations in the large-scale adoption of windmills in pumping. In general, the most suitable applications of windmills are at places which are (1) windy, (2) away from the source of supply of electrical power, and (3) too remote to obtain petroleum fuels at a reasonable cost.

Pumps run by electric motors and diesel or petrol (gasoline) engines are usually less expensive than windmills of comparable capacity. Savings in fuel cost by using windmills may, however, make up the difference in capital cost between windmill pumping sets and engine or motor operated ones, if the fuel is expensive. Engines and electric motors have the advantages of compactness and high capacity. However, major interruptions in the supply of electricity and limitations in the availability of diesel or other petroleum fuels favour the use of wind energy in pumping, especially on small land holdings.

The minimum wind speed required for the operation of windmill usually ranges from 6 to 8 km/h, depending on the design. The anticipated windiness of a location is to be considered before a decision is made on the installation of windmills The relative windiness of different regions could be broadly compared from the average wind speeds. The energy from the wind varies as the cube of the wind velocity and the duration of wind at a particular velocity. Therefore, two places having the same monthly average wind speed may vary greatly in their wind-energy potential. Thus, reliable estimates on the wind energy potential of a location would require wind velocity-duration data.

Figure 13.1 presents the wind maps of India, showing the average wind velocities for the months of January, March, May and July. It may be seen that regions of maximum wind velocities are the coastal areas and the arid and semi-arid zones. Further, the period of high wind velocity is mainly the summer months. This period, however, is not the main crop-growing season, even though summer vegetables and fodder crops can be grown successfully during these months. The average wind velocity in India varies from 10 to 20 km/h, as compared to about 25 km/h in the Netherlands, Australia or Canada. Hence, the cost of developing wind power will be substantially higher in India than in the countries mentioned above.

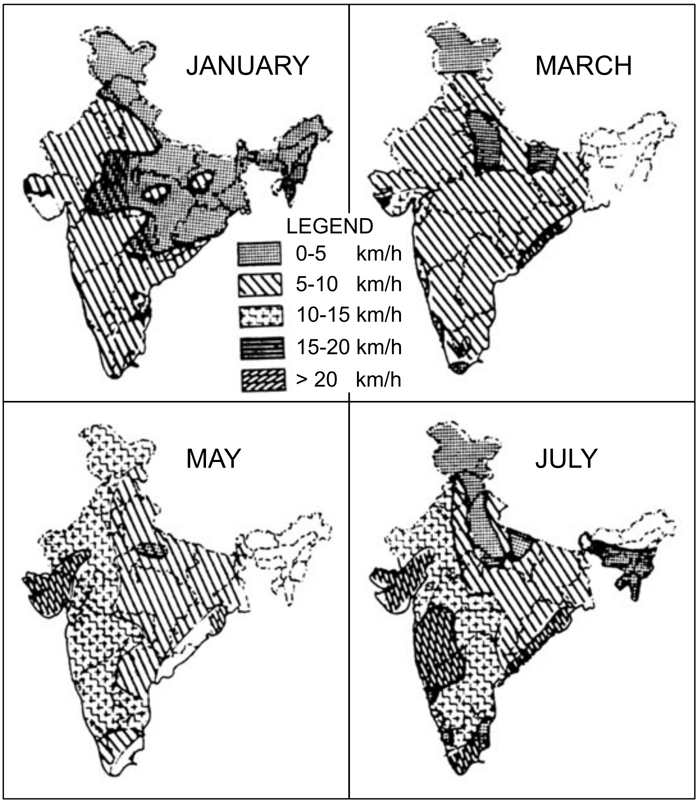
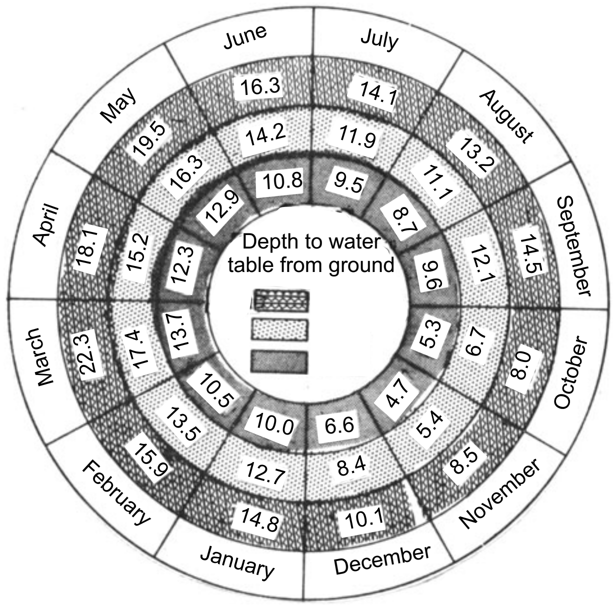


Fig. 13.1 Wind maps of India showing average wind velocities for the months of January, March, May and July.

Based on: Bulletin No. 3, Indian National Science Academy, Proc. Symposium on Ground and Lake Water Reservoirs of India, 1970

Too strong winds also pose problems in wind-energy utilization. Some coastal areas experience tropical cyclones. For example, in the Philippines, most places with high mean wind speeds have a high incidence of cyclones. This calls for suitable designs of windmills, which can withstand the cyclones, including provision for dismantling components easily before cyclones strike and their reinstallation later.

The widely varying characteristics of winds in different regions call for the development of specific designs of windmills to suit the range of average wind velocities. Studies on the characteristics of winds in a region should include data on the number of windy days in a year and the range in wind velocities during the day. The minimum wind velocity to initiate the operation of a windmill ranges from 6 to 8 km/h for commercially available windmills. The water yields of windmill-operated pumping sets vary with the diameters of the rotors, other design characteristics and depths to water tables. Figure 13.2 presents predicted yields of windmill pumps in different months in a year, based on the wind characteristics prevailing in Delhi, and at different depths to water table.



Note: All figures in hectare-centimetres

Fig. 13.2 Estimated monthly yield of water from a windmill pumping system at Delhi (Kumar *et al*. 1981)

13.1.2 Power from Windmills

The power developed by a windmill is a function of the average wind velocity at the windwheel or rotor, the area swept by the wheel and the density of the air mass. The following are the basic relationships:

(i) Wind power is proportional to the density of air.
(ii) Wind power is proportional to the area swept by the rotor.
(iii) Wind power is proportional to the cube of wind velocity.

A wind rotor can extract power from the wind because it slows down the wind, neither too much nor too little. At standstill, the rotor will not produce any power. At very high speeds of the rotor, the air is more or less blocked by the rotor and no power is produced. In between the two extremes, there is an optimal rotational speed where the power extraction is at a maximum. The power developed by a wind rotor is a function of its rotational speed at a given wind speed. Similarly, the torque produced by a rotor is a function of its rotational speed. The wind veolocity at the rotor is the average of the wind velocities between the front and the rear sides of the rotor and may be expressed as follows:

$$v = \frac{v_1 + v_2}{2} \tag{13.1}$$

where, v = wind velocity at rotor, m/s
v_1 = wind velocity at the rotor on the windward side, m/s
v_2 = wind velocity at the rotor on the leeward side, m/s

The rate of flow of air mass at the rotor may be expressed by the following relationship:

$$\bar{m} = \rho a v \tag{13.2}$$

The power developed by a windmill is the difference between the kinetic energies produced in the front and the rear of the rotor, per unit time.

$$E = \frac{1}{2} m v_1^2 - \frac{1}{2} m v_2^2$$

$$= \frac{1}{2} m \left(v_1^2 - v_2^2\right) \tag{13.3}$$

where, E = kinetic energy at the rotor, $j \left(\frac{\text{kg m}^2}{s^2}\right)$

m = mass of the air, kg

Since $\bar{m}$ in Eq. (13.2) is the rate of flow of the air mass, i.e. mass per unit time, it may be substituted in Eq. (13.3) to obtain the kinetic energy per unit time (joules/second or watts), which is the power developed by the rotor. Thus,

$$P = \frac{1}{2} \rho a v \left(v_1^2 - v_2^2\right) \tag{13.4}$$

where, P = power developed by the windmill, watt

Substituting the value of v from Eq. (13.1)

$$P = \frac{1}{2} \rho a \left(\frac{v_1 + v_2}{2}\right)\left(v_1^2 - v_2^2\right)$$

Simplifying,

$$P = \frac{\rho a v_1^3}{4}\left(1 + \frac{v_2}{v_1}\right)\left\{1 - \left(\frac{v_2}{v_1}\right)^2\right\} \tag{13.5}$$

The maximum value of power, P_{max}, may be obtained by differentiating Eq. (13.5) and equating it to zero, as follows:

Let, $\frac{v_2}{v_1} = x$

Therefore, $\frac{dP}{dx} = \frac{\rho}{4} a v_1^3 \; \{(1 + x)(-2x) + (1 - x^2)\, 1\} = 0$

Then $-2x - 2x^2 + 1 - x^2 = 0$

$$-3x^2 - 2x + 1 = 0$$

or $(3x - 1)(x + 1) = 0$

Therefore, $x = 1/3$ (since x cannot be -1)

Thus, P_{max} occurs when $v_2/v_1 = 1/3$
Substituting this relationship in Eq. (13.5)

$$P_{max} = \frac{\rho a}{4} v_1^3 \left(1 + \frac{1}{3}\right)\left\{1 - \left(\frac{1}{3}\right)^2\right\}$$

$$= \frac{8}{27} \rho a v_1^3 \qquad (13.6)$$

It may be seen that the maximum power developed by a windmill varies directly as the cube of the wind velocity.

Ideal Efficiency of Windmills

Theoretically, the power available from a moving air mass may be estimated as follows:

Air mass passing in unit time over an area $a = \rho\, a\, v_1$

The kinetic energy of the air mass $= \frac{1}{2} (\rho\, a\, v_1) \left(v_1^2\right)$

The ideal efficiency of a windmill is the ratio of the maximum power developed to the theoretical power available, and may be expressed as follows:

$$= \frac{8}{27} \rho a v_1^3 \div \frac{1}{2} \rho a v_1^3$$

$$= \frac{16}{27}, \quad \text{or} \quad 59.26\%$$

Example 13.1 Estimate the horse power developed by a windmill having a rotor of 5 m diameter, when the wind speed is 10 km/h. The density of air may be assumed to be 1.293 kg/m^3.

Solution

Power output,

$$P_{max} = \frac{8}{27} \rho a v_1^3$$

$$a = \frac{\pi D^2}{4} = \frac{\pi}{4} (5)^2$$

$$= 19.625 \text{ m}^2$$

$$v_1 = 10 \text{ km/h} = 2.77 \text{ m/s}$$

$$P_{max} = \frac{8}{27} \times 1.293 \times 19.625 \times 2.77^3$$

$$= 160 \text{ watts}$$

$$= 0.214 \text{ hp}$$

EXAMPLE 13.2 A windmill is to be designed to develop 0.60 hp at a wind speed of 20 km/h. Determine the diameter of the rotor.

Solution

$$P_{max} = \frac{8}{27} a \rho v_1^3 \text{ watts}$$

$$= 0.60 \times 746 = 447.6 \text{ watts}$$

$$v_1 = 20 \text{ km/h} = 5.55 \text{ m/s}$$

Substituting the above values in Eq. (13.6),

$$447.6 = \frac{8}{27} \times 1.293 \times a \times (5.55)^3$$

$$\therefore \quad a = \frac{447.6 \times 27}{8 \times 1.293 \times (5.55)^3}$$

$$= 6.834 \text{ m}^2$$

Diameter of rotor, $d = \sqrt{\frac{4a}{\pi}} = \sqrt{\frac{4 \times 6.834}{\pi}} = 2.95$ m

EXAMPLE 13.3 Determine the power output of a windmill having a rotor of diameter 5 m, at a wind velocity of 20 km/h on the windward side and 10 km/h on the leeward side. Density of air is 1.293 kg/m^3.

Solution

$$P = \frac{\rho a}{4} v_1^3 \left(1 + \frac{v_2}{v_1}\right) \left\{1 - \left(\frac{v_2}{v_1}\right)^2\right\}$$

$$\rho = 1.293 \text{ kg/m}^3$$

$$v_1 = 20 \text{ km/h}$$

$$= 5.55 \text{ m/s}$$

$$v_2 = 10 \text{ km/h}$$

$$= 2.77 \text{ m/s}$$

$$a = \frac{\pi}{4} \times 5^2$$

$$= 19.625 \text{ m}^2$$

Substituting the above values,

$$P = \frac{1.293 \times 19.625}{4} (5.55)^3 (1 + 0.5) \{(1 - (0.5)^2\}$$

$$= \frac{1.293 \times 19.625}{4} (5.55)^3 (1.5) (0.75)$$

$$= 1220 \text{ watts}$$

$$= 1.63 \text{ hp}$$

13.1.3 Windmill Tower

The tower of the windmill is designed according to the height and the maximum force that can be exerted on the rotor. The force exerted by the air on the rotor in the axial direction may be expressed as follows:

$$F = \bar{m}\, v_1 - \bar{m}\, v_2$$

$$= \bar{m}\,(v_1 - v_2)$$

where, F = force exerted on the rotor, kg

Since $\bar{m} = \rho\, a\, v$

$$= \rho\, a \left(\frac{v_1 + v_2}{2} \right)$$

$$F = \frac{\rho a}{2} \left(v_1^2 - v_2^2 \right) \tag{13.7}$$

The radial force would be maximum when $v_2 = 0$. The windmill tower is designed to withstand this condition, i.e.

$$F = \frac{\rho a}{2} v_1^2$$

Thus, the stress on the windmill tower varies as the square of the wind velocity.

13.1.4 Site Selection for Windmills

The power output of a windmill increases with the cube of the wind speed. Hence, the site for a windmill must be chosen carefully to ensure that the location with the highest wind speed in the area is selected. Site selection is rather easy in flat terrain, but is more difficult in hilly or mountainous terrains. The major factors influencing the selection of a suitable site for installing a windmill are wind shear, turbulence and wind acceleration.

Wind Shear

The wind slows down near the ground to an extent determined by the surface roughness. Vegetation, buildings and the ground itself cause the wind to slow down near the ground. The wind speed increases with increasing height. The rate of increase with height depends upon the roughness of the terrain. For various types of terrain, the roughness height z_0 are as follows (Lysen, 1982):

Flat land	: Beach, ice, snow landscape	z_0 = 0.005 m
Open ground	: Low grass, airports, empty crop land	z_0 = 0.03 m
	: Low crops	z_0 = 0.10 m
Rough ground	: High crops, trees	z_0 = 0.25 m
Very rough ground	: Forests, orchards	z_0 = 0.50 m
Closed areas	: Villages, subrubs	z_0 = 1.0 m

The above values of roughness height z_0 may be used to determine the wind velocity at any desired height, under a specified ground surface condition based on the wind velocity values obtained at a specified height from a meteorological station in the area, using the following relationship:

$$\frac{z_r^{v_z}}{z^{v_{z_r}}} = (z_0)^{v_z - v_{z_r}} \tag{13.8}$$

where,

v_z = wind velocity at any required height, km/h

v_{z_r} = wind velocity at a reference point, km/h

z = height at which the wind velocity is to be estimated, m

z_r = height of the reference point, m

z_0 = roughness height, m

The term $(z_0)^{v_z - v_{z_r}}$ is called the *wind shear roughness coefficient.* From (Eq. 13.8)

$$\left(\frac{z_r}{z_0}\right)^{v_z} = \left(\frac{z}{z_0}\right)^{v_{z_r}}$$

or

$$v_z \ln\left(\frac{z_r}{z_0}\right) = v_{z_r} \ln\left(\frac{z}{z_0}\right)$$

or

$$\frac{v_z}{v_{z_r}} = \frac{\ln (z/z_0)}{\ln (z_r/z_0)} \tag{13.9}$$

Example 13.4 Estimate the wind velocity at a height of 7 m from open ground without crops. The wind velocity, as observed at a meteorological station in the area, at a reference point of 10 m height is 20 km/h.

Solution

Roughness height, z_0 = 0.03 m

Height at which the wind velocity is required = 7 m

Height of reference point, z_r = 10 m

Wind velocity at reference point, v_{z_r} = 20 km/h

Adopting Eq. (13.9),

$$\frac{v_z}{v_{z_r}} = \frac{\ln (z/z_0)}{\ln (z_r/z_0)}$$

$$\frac{v_z}{20} = \frac{\ln (7/0.03)}{\ln (10/0.03)}$$

$$\frac{v_z}{20} = \frac{5.452}{5.809}$$

$$v_z = 18.77 \text{ km/h}$$

Turbulence

Winds flowing around buildings or over very rough surfaces including shelter belts, exhibit rapid changes in speed and/or direction, called turbulence. This turbulence decreases the power output of the windmill and can also lead to unwanted vibrations of the machine (Fig. 13.3). The turbulence is felt upto a leeward distance of 15 to 20 times the height of the buildings/trees. The region of influence also extends to windward, about five times the height of the obstruction.

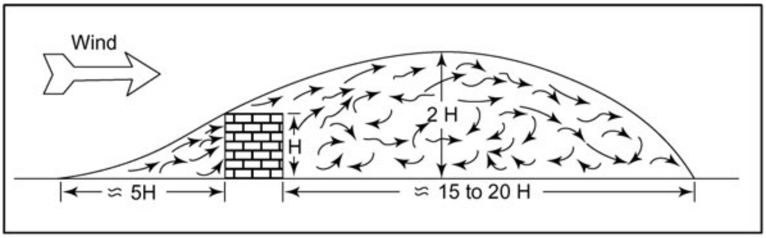


Fig. 13.3 Zone of air turbulence over a small building or a shelter belt

Wind Acceleration Over Ridges

The tops of ridges experience higher wind speed due to the effect of wind shear. Ridges also act as concentrators of the air stream (Fig. 13.4) causing air to accelerate near the top. The effect is strong when the ridge is smooth, and neither too steep nor too flat. The ideal slope angle varies from 6° to 16°. For an ideal location of the windmill, orientation of the ridge should be perpendicular to the main wind direction.

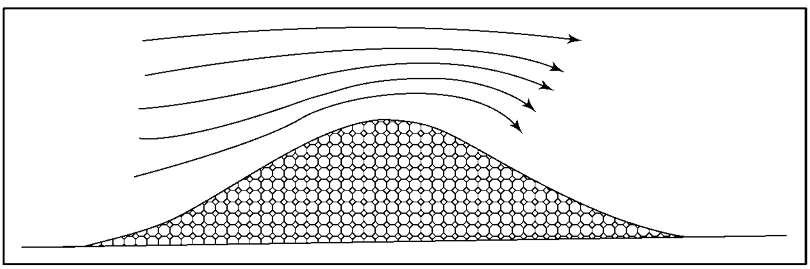


Fig. 13.4 Acceleration of wind over a ridge

The above points reveal that the distribution of wind velocity over the ground surface is a major consideration in designing the height of windmill towers. There will be a substantial loss in power if the rotors are not placed at a sufficient height. Excessive heights, however, make the cost of the windmill prohibitive. For effective utilization of wind, the height of the tower should normally be over 6 m. Similarly, it is important to locate the windmill clearly away from the influence of obstacles like buildings and trees, and preferably on ridges and not in depressions.

13.1.5 Types of Windmills and their Construction

Windmills vary from relatively simple home made contrivances to well-designed factory made products. Based on the axis of rotation, windmills may be classified into two groups, namely, vertical-axis and horizontal-axis rotational machines. In each group, there are wide variations in design and choice of construction materials.

Vertical-Axis Windmill

The common type of vertical-axis windmill is the cylinder-type mill, often referred to as 'Savonius rotor' in Western literature. The savonius rotor (Fig. 13.5) consist of a 200-litre drum, cut half longitudinally. The halves are offset by about two-thirds of their diameter. When fixed to a vertical shaft, the wind will flow into one half, creating a rotating moment and then 'spill' into the other half cylinder, causing a similar effect. Savonius rotors rarely attain efficiencies above 31 per cent, but due to their easy construction they have application in developing countries. The anemometer-type windmill shown in Fig. 13.6 is also easy to construct, using cylinder havles, and is functional in wind from any direction.

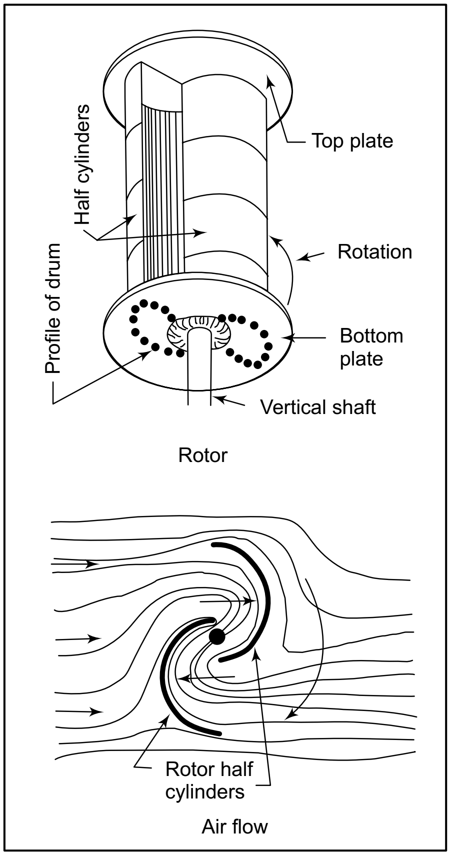


Fig. 13.5 A Savonius rotor made of half cylinders cut from a 200-litre oil drum. The figure at the bottom shows the air flow pattern around the rotor
Adapted from: Wood *et al.* (1977)

Horizontal-Axis Windmill

Horizontal-axis windmills (Figs 13.7 to 13.9) are the most commonly used in water lifting. The common types of horizontal-axis windmills are the traditional Dutch windmill and the modern propeller and the multi-vane fan-type windmills. The Dutch windmill, now almost obsolete, consists of four slatted fans covered with cloth and fastened to a horizontal axle working on a turn-table which permits the direction of the axis to change with wind direction.

Propeller-Type Windmill

Propeller-type windmills (Figs. 13.8 and 13.9) are aerodynamically most efficient. They are usually used to operate wind-powered electric generators. The number of blades ranges from 2 to 4. They are moved mainly by aerodynamic lift forces. A tail vane automatically orients the rotor to the direction of wind. The propeller is gradually turned out of the direction of wind, when the wind velocity exceeds about 35 km/h. Table 13.1 presents the power output of typical factory-made propeller-type wind mills of different rotor diameters, at different wind velocities.

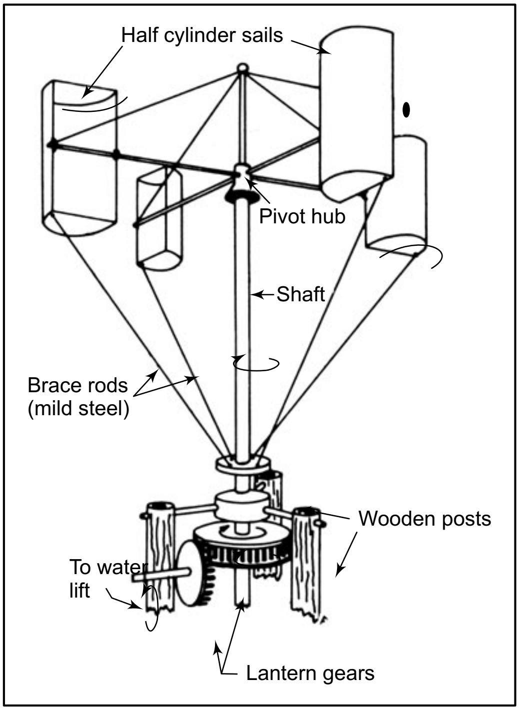


Fig. 13.6 Anemometer-type windmill with lantern gear
Adapted from: wood *et al*. (1977)

TABLE 13.1 Windmill Power Output in Watts (assuming 70% of theoretical efficiency)

Propeller diameter, m	Wind velocity, km/h 8	16	24	32	40	48
0.6	0.6	5	16	38	73	131
1.2	2	19	64	150	300	520
1.8	5	42	140	340	660	1,150
2.4	10	75	260	610	1,180	2,020
3.0	15	120	400	950	1,845	3,180
3.6	21	170	540	1,360	2,660	4,600
4.2	29	230	735	1,850	3,620	6,250
4.8	40	300	1,040	2,440	4,740	8,150
5.4	51	375	1.320	3,060	6,000	10,350
6.0	60	475	1,600	3,600	7,360	12,760
6.6	73	480	1,940	4,350	8,900	15,420
7.2	86	685	2,300	5,180	10,650	18,380

Source: Clews, H. Electric Power from the Wind, Solar Wind Co., Maine 1973, p. 4. (*Adapted from* Fritz, M., 1982)

Locally-made propeller-type windmills are sometimes used to operate water ladders in Thailand and other South-East Asian countries (Fig. 13.8).

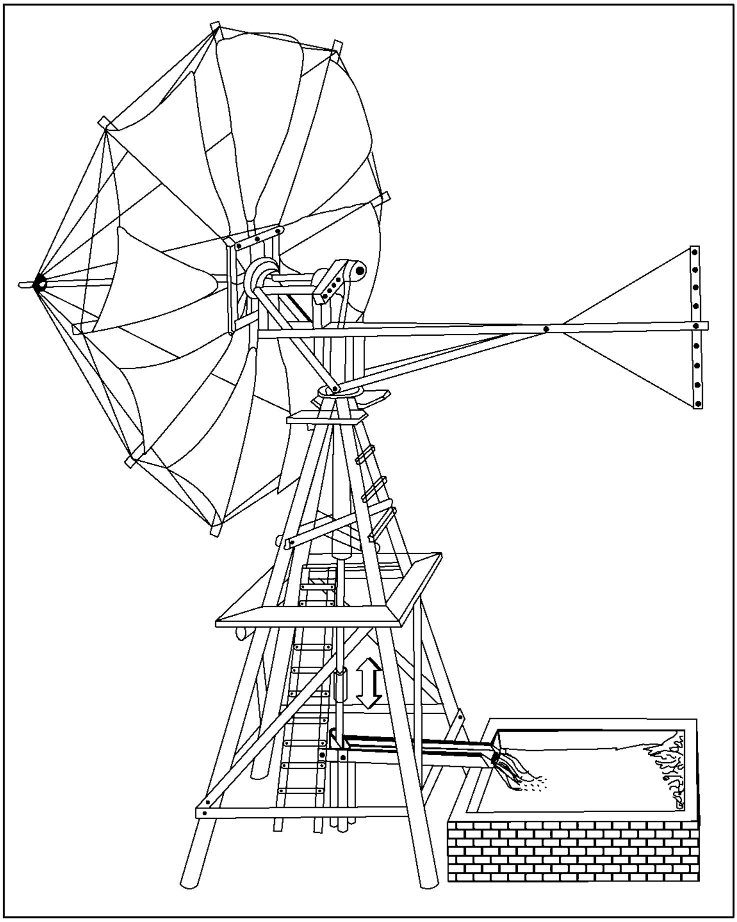


Fig. 13.7 A sail-type windmill (often called Cretan windmill) made of wooden frame and canvas sails for the rotor

Factory-made propeller-type windmills (Fig. 13.9) develop high rotational speeds and dynamic stresses, leading to higher requirements of skill in manufacturing and maintenance. Their high speeds tend to reduce their adaptability to pumping with piston pumps or indigenous water lifts.

Multi-Vane Windmill

Mult-vane type windmills are commonly used for pumping water. They range from simple cloth-sail windmills to highly sophisticated factory made multi-vane fan-type mills (Figs. 13.10 to 13.12). They consist of a rotor mounted on a horizontal shaft and a tower on which the rotor works, a power transmission mechanism and a water lifting device. The towers of home made windmills are usually made of bamboo poles and wood. The sails may be of cloth or wood. Wood and cloth material, in windmill construction, are associated with low cost, high rate of breakdown and high maintenance costs.

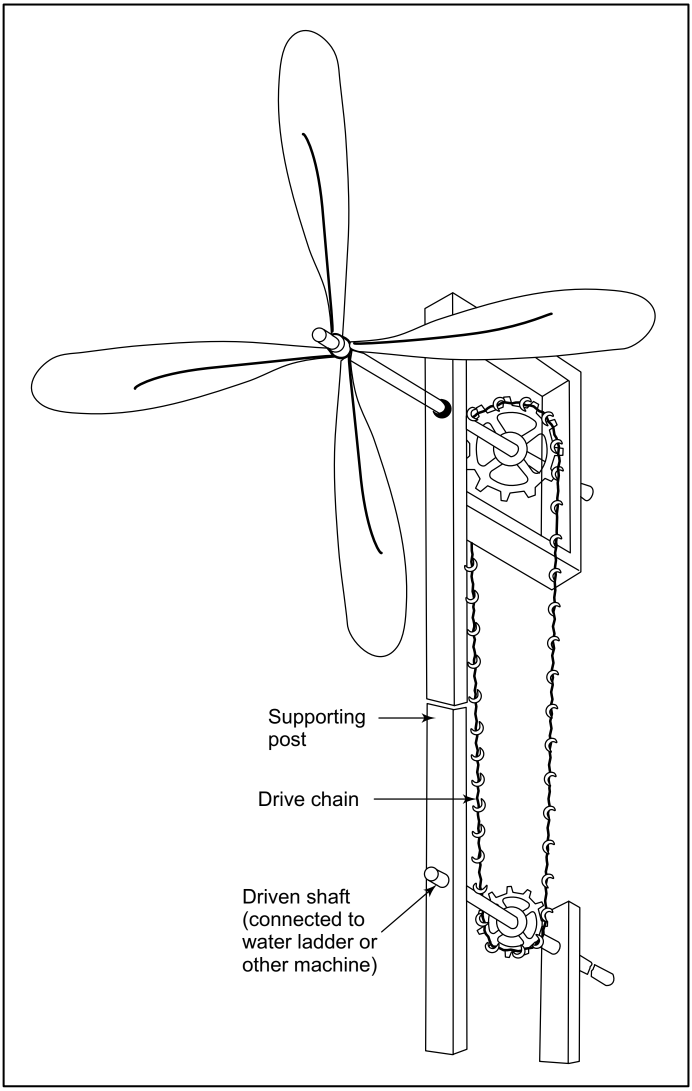


Fig. 13.8 A locally made propeller type windmill suitable for operating water ladders and other simple machines

Home made windmills commonly used in South-East Asia are constructed by placing 8 to 12 bamboo spokes on a hardwood axle. The rim is formed by a rope or wire fastened to the outer ends of the spokes. Triangular pieces of cloth or matting are fixed to the spokes and the rim to form the sails. The wheel is about 5 m in diameter. The axle on which the wheel is fixed is supported at its two ends by two hardwood posts. The windmill is usually used to operate indigenous water ladders. Power is transmitted from the wheel to the water ladder through a simple chain drive. Improved locally-made windmills use corrugated galvanized-iron sheets for blades and steel pipes for posts. The number of blades is usually 6.

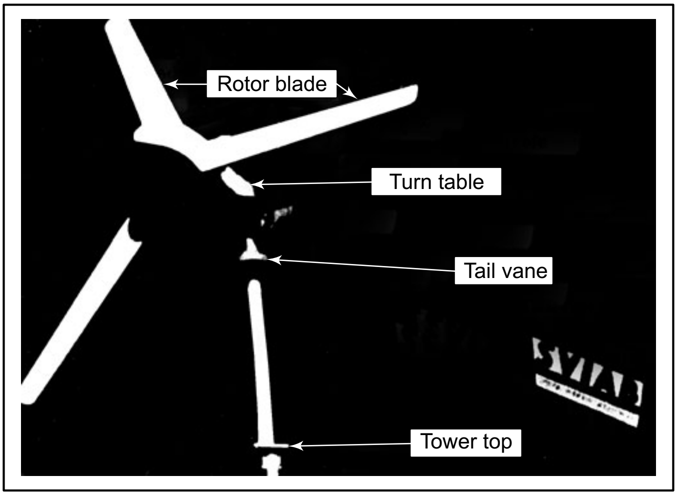


Fig. 13.9 Rotor of a factory made propeller-type windmill
Courtesy: SVIAB, Swedish Windpower Industries Ltd., Bergshan, Sweden (Anon., 1982d)

Factory made, multi-vane type windmills are designed to meet the performance requirements and structural strength adequately. Figures 13.10 to 13.12 illustrate the constructional detail of the windwheel. Well designed windmills will work for long periods (20 to 30 years) without much attention, and the maintenance costs are very low. Their strength and automatic speed governing mechanisms enable them to withstand major storms.

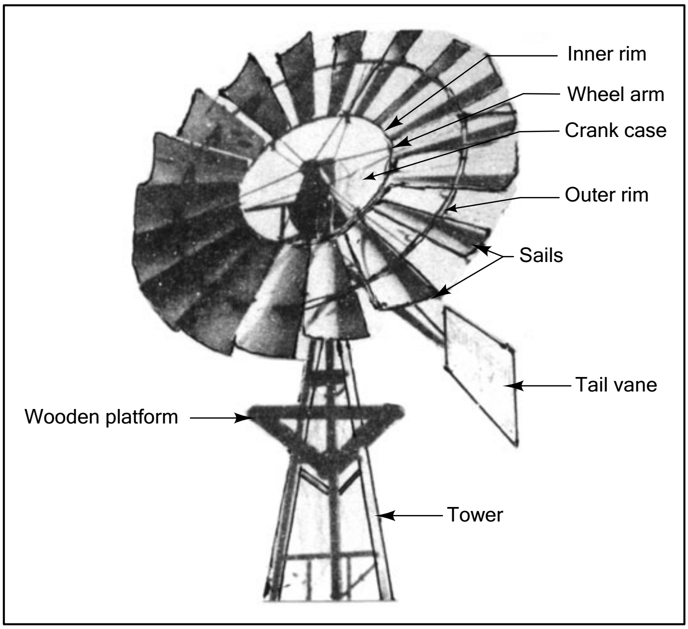


Fig. 13.10 Windwheel and head of tower of a multi-vane type windmill

The diameters of windwheels range from 4 to 10 m. The sails are usually made of galvanized steel. The tail vane orients the windwheel to the prevailing wind direction. The mills turn into the wind on a steel turntable working on large ball bearings. The crank and connecting-rod assembly changes the rotating motion of the wheel to reciprocating motion, for direct connection to a piston pump. The swivel of the connecting rod assembly permits the working parts to rotate with the mill head on the turntable. A pullout mechanism permits the machine to be locked against rotation. Most windmills are designed to turn out of wind or become inefficient when the wind speed increases beyond a critical value which usually ranges from 30 to 40 km/h. (For detailed procedures for the design of multi-vane windmills, refer Lysen (1982)).

The LORP windmill, available commercially in India, is a comparatively low-cost machine (Fig. 13.11). It has 12 blades with a rotor diameter of 5 m. The height of the tower is 7 m. The minimum speed to initiate operation is 8.5 km/h and the cut-off speed is 35 km/h. Table 13.2 shows the discharge capacity of the windmill pump at different wind velocities.

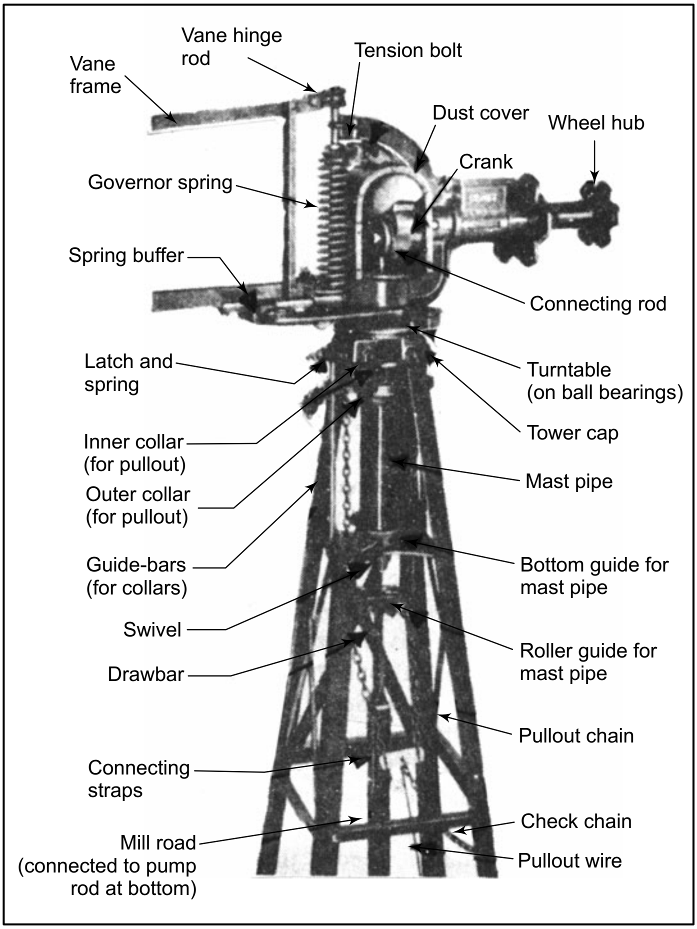


Fig. 13.11 Close view of a multi-vane type windmill head after wind wheel and tail vane are removed and showing the cut-away view of crank case

Courtesy: Sidney Williams and Co. (Pvt.) Ltd (Anon., 1970)

Safety Systems in Windmills

Appropriate safety devices, form an essential part of windmills. Windmills without a safety system usually have a short life. The history of wind energy is scattered with tragic incidents with windmills blown into pieces because safety systems were not present or were badly designed. At high wind speeds, the bending moment on the blades becomes too high and eventually they break. In the case of windmills with weak towers, the tower might fail even before the rotor blades actually crumble.

The safety systems can act either on the rotor as a whole or on each of the blades. The first method is usually employed with the multi-blade rotors, such as those on water pumping windmills. The second is usually used in propeller type windmills. The *hinged vane system* of safety device is usually adopted in vertical axis windmills. The wind rotor can be pushed out of the wind by two auxillary vanes attached to the head of the windmill by placing the rotor eccentric with respect to the vertical rotation axis of the head. The function of the safety system with an inclined hinged vane is to limit the rotational speed of the rotor and to limit the axial forces acting upon the rotor. This is accomplished by turning the rotor gradually out of the wind, with increasing wind speed. As the vane remains more or less parallel to the wind, the turning of the head requires that the vane is turned around its inclined hinge, thereby being lifted. With increasing wind speed the aerodynamic forces on the rotor and auxillary vane increases, thus turning the rotor further out of wind.

TABLE 13.2 Discharge Capacities of LORP Windmill at Different Wind Velocities

Wind velocity	**Discharge**	
km/h	**m^3/h**	**l/s**
7-11	3.6	1
11-14	5.4	1.5
14-18	7.2	2
18-22	10.8	3
22-25	14.4	4
25-29	18.8	5
29-32	21.6	6

Adapted from: LORP Windmill Project Report (Anon., 1982e)

13.1.6 Windmill Pumps

Windmills could be applied to draw water from various sources such as rivers, canals, lakes, open wells and tube wells. They are located directly above the source of water or very close to it, in order to minimize power loss in transmission. The type of water-lifting device depends on the source of water. Water ladders and chain pumps are used for high-volume, low-head lift, utilizing locally made windmills. Positive-displacement type piston suction pumps are commonly used with multi-vane type windmills, for pumping from open wells or tube wells, and from rivers or lakes when the head does not exceed 6 m. A piston-type lift pump (Fig. 13.13) is usually used for deep wells, the pump being located inside the well, directly underneath the windmill and below the water table. The centrifugal pump which is to run within the limits of the design speed range, is not suitable for use with windmills which run at variable speeds depending on the velocity of the wind.

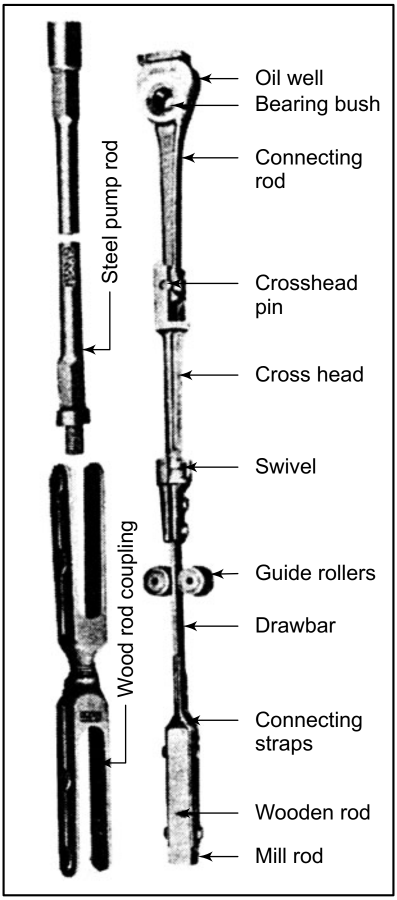


Fig. 13.12 Connecting rod assembly and parts of a typical windmill
Courtesy: Sidney Williams and Co. (Pvt.) Ltd. (Anon., 1970)

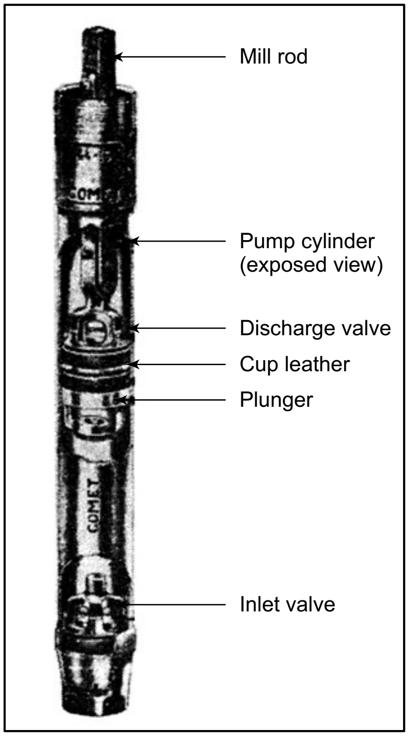


Fig. 13.13 Plunger pump commonly used with windmills. Cut-away view of a section of pump cylinder shows the plunger and valves
Courtesy: Sidney Williams and Co. (Pvt.) Ltd. (Anon., 1970)

13.1.7 Selection of Windmill

The type of windmill to be selected depends on the nature of the load and the wind. A compromise is often attempted between simplicity and ruggedness of the machine on the one hand, and efficiency on the other. Locally made windmills are associated with low cost and poor efficiency. They cannot withstand storms and may require frequent repair. Their main advantages are low cost and adaptability to local skills in construction and maintenance. Commercial multi-vane windmills have the advantage of delivering high torque even at low wind velocities. This is a desirable feature in using piston pumps.

13.1.8 Installation and Maintenance of Windmill Pumping Systems

Windmills are installed directly over shallow tube wells, with their legs anchored on well-built masonry/concrete foundations. In case of small diameter open wells, it is necessary to install two steel beams (R.S. joists) supported on concrete/masonry foundations on which the windmill is installed. In case of large open wells, it is necessary to have a cantilever platform, supported on the one side, with steel beams projecting into the open well. The windmill is installed on the projected portion of the platform. It is to be ensured that the pump is in proper alignment, as otherwise there will be frequent breakage of the connecting rod.

The main parts which get worn out quickly are the cup leather washers in the pump cylinder. Sufficient spares of the washers and connecting rod hooks and couplings should be kept handy.

Storing the Pumped Water

Wind is an intermittent source of power. Windmills work day and night, whenever the wind velocity exceeds the minimum value required for turning the wheel. Provision for storage of the pumped water is, therefore, an essential part of a windmill irrigation system in most areas. A masonry tank above ground level is usually the most desirable storage structure.

When the land to be irrigated lies at a lower level, the tank can be constructed partly dug and partly above ground level (Fig. 13.14). The capacity of the tank should preferably be adequate to store the accumulated discharge of 2 or 3 days. An outlet pipe provided with a sluice valve is used to take out water from the tank for irrigation.

Fig. 13.14 A typical windmill installation for irrigation. Note the water storage tank in the foreground

13.2 HYDRO-POWER

Water power could be utilised in pumping through micro-turbines and hydraulic rams. All water power applications involve harnessing energy from falling or flowing water. The power P in watts available from a flow of Q litres/sec of water falling through a head of H metres is:

$$P = 9.81 \times Q \times H$$

in which the constant 9.81 is the gravitational constant (or acceleration due to gravity). If Q is expressed in m^3/sec, then the above formula gives P in kW. Thus, 9.81 kW of power is available in a flow of 1 m^3/sec per metre drop. The actual power output, however, will be reduced by the system efficiency. For example, a system with 50 per cent efficiency will convert half the available power. The efficiency of water-powered devices is usually high. The efficiency of a well designed micro-turbine could be about 70 per cent while that of a hydraulic ram is 30 to 60 per cent (hydraulic output).

The main shortcoming of water power as an energy source is that it is available for convenient use only in a limited number of locations where the flows and heads are adequate. Further, many of the regions where hydro-potential could be effectively harnessed have high rainfall and hence irrigation may be a low priority item. In spite of the above shortcomings there are many regions where rainfall is seasonal and irrigation during dry seasons would be highly beneficial to seasonal crops, orchards and plantations. Though stream flows are low in dry seasons, many hill regions (like the Himalayan region) provide adequate hydro-power potential during the dry season.

Hydro-powered systems usually have a high power to size ratio and hence a favourable power to cost ratio. They are also mechanically simple and robust. Hence, they have long working lives and require only limited maintenance. As a result, hydro-power is one of the most economic sources of power in areas where the resource is available.

There are different types of water turbines to suit different situations. Turbines can be broadly classified into the following three groups:

	Head	*Type of turbine*
a.	Low	Propeller/Kaplan
b.	Medium	Banki/Francis
c.	High	Pelton/Turgo

Fixed blade propeller type turbines are often used in micro hydro-systems. They are only moderately efficient when the flow rate varies substantially. In situations where variable flow and power are needed the turbine runner may have adjustable pitch blades, as in a Kaplan turbine. However, adjustable pitch runner blades are expensive and hence are usually applied only in large installations.

13.3 HYDRAULIC RAM

The hydraulic ram, sometimes abbreviated *hydram*, is a simple automatic device which utilizes the kinetic energy of water falling a moderate height to raise a part of it to a much greater height (Figs. 13.15 and 13.16). The device can be used wherever a stream of water flows with a minimum of about 1 m fall in altitude. The first working model of a hydraulic ram was devloped by Montgolfier in the year 1796. Like the windmill, the hydraulic ram experienced a period of popularity in industrialised countries, followed by a decline due to the large-scale development in generation and distribution of economical electrical energy. In developing countries, however, the difficulty in conveying electrical energy to remote hilly areas and the shortage of petroleum fuels have focussed the importance of hydraulic rams for small-scale lift irrigation and rural water supply.

Hilly areas are often deprived of irrigation facilities due to uneven topography and non-availability of conventional sources of energy. Studies at the State Planning Institute, Lucknow, have established the techno-economic feasibility of hydraulic rams as a potential means of irrigation in the hill districts of Uttar Pradesh. Hydraulic rams could also be used with advantage in the hilly regions of most states in India and other developing countries. The source of supply of water for operating a hydraulic ram may be a stream, a spring or an irrigation canal. In the mountainous regions of India and other developing countries, there are numerous sites where hydraulic rams could be installed, thus reducing human drudgery in carrying head-loads of drinking water along steep hills, or turning unproductive and unused lands to efficient farming units (Fig. 13.17 and 13.18). The simplicity of construction and the automatic operation of the hydraulic ram make it especially adapted to remote rural areas which often have problems of non-availability of commercial energy sources such as electricity and diesel and lack of skilled technicians for maintenance and repair of engines/motors and pumps.

Specific Applications of Hydraulic Rams

The following are some of the specific uses to which hydraulic rams could be applied:

1. To lift a part of the flow of hillside spring, stream or rivulet to irrigate adjacent slopy lands (Fig. 13.15).

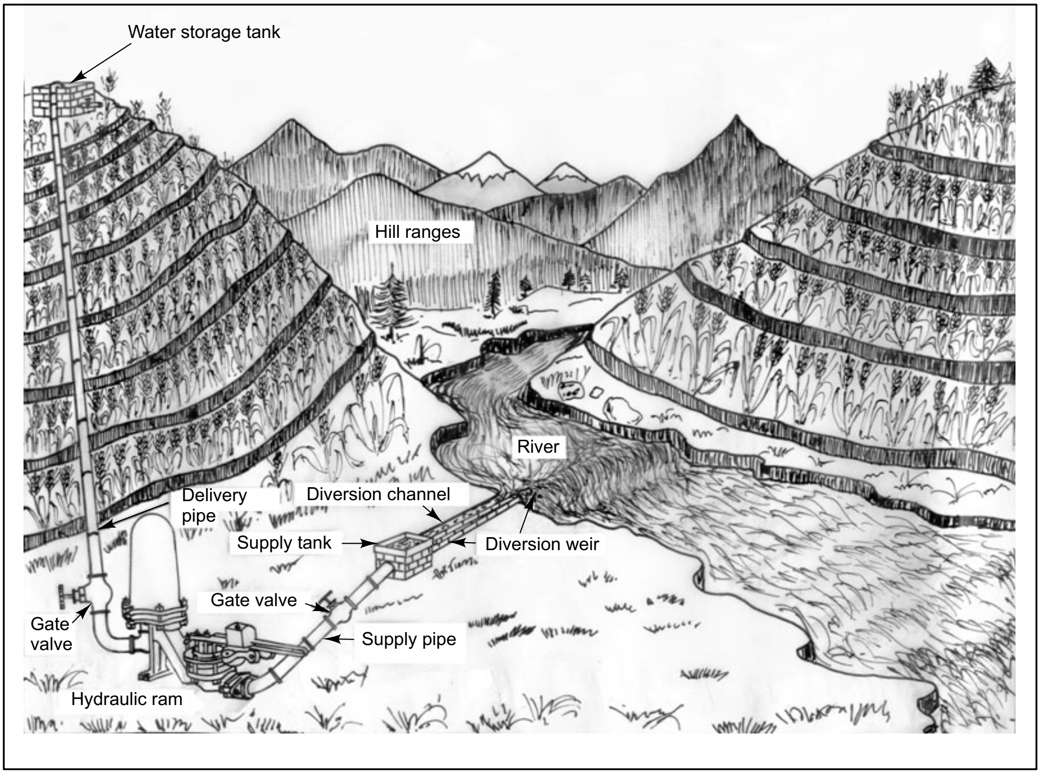


Fig. 13.15 A panoramic view of a hydraulic ram installed to irrigate a hilly area. Note the barren hillock on the opposite side which does not have irrigation facility. The vegetation on the hill illustrates appropriate land use, comprising of forest in the top reach, orchard (irrigated by the drip system) in the middle and grain crop in the lower reach which is levelled in contour benches. *Note* the provision of a separate hydrant to irrigate the lower reach. The water supply during the night is stored in the tank above to be used to irrigate the orchard through drip/low pressure sprinkler system

2. To lift water for drinking water supply in villages (Fig. 13.16).
3. To provide water supply to small industrial establishments and fish ponds located in hilly areas.
4. To feed water to a high-level field channel by installing the ram downstream of a weir (*anicut*) or drop structure in a canal system. This will increase the command area (C.C.A.) of a canal system (Fig. 13.17).
5. To boost the discharge of lift irrigation schemes using engine or electric-motor-operated pumping sets, to take a part of the pump discharge to higher elevations for irrigation (Fig. 13.18).

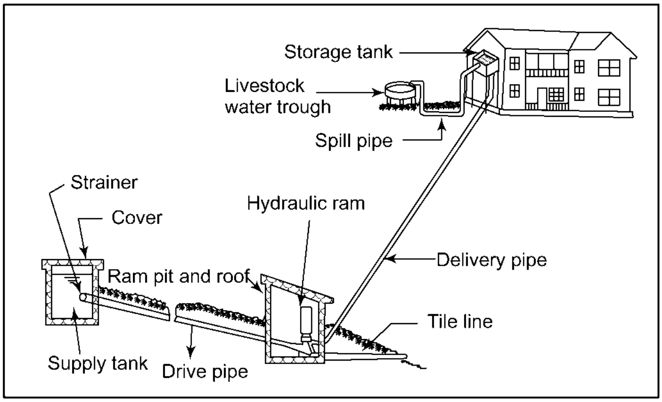


Fig. 13.16 Installation of a hydraulic ram for domestic water supply in a hilly region

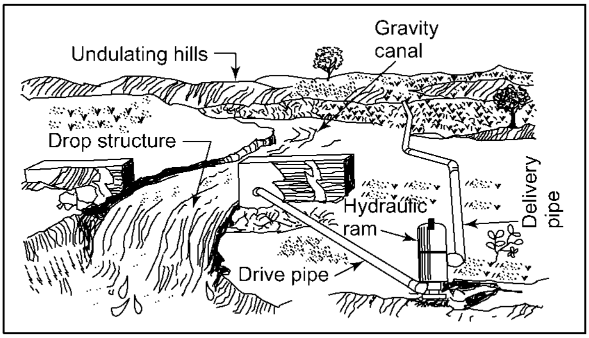


Fig. 13.17 Schematic sketch illustrating the installation of a hydraulic ram at a canal drop
Courtesy: Premier Irrigation Equipment Pvt. Ltd. (Anon., 1982b)

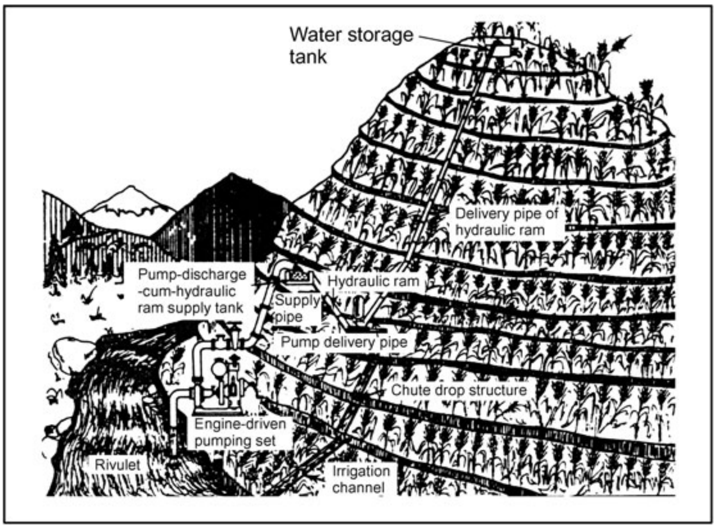


Fig. 13.18 Schematic sketch illustrating conjuctive use of an engine-driven pumping set with a hydraulic ram to irrigate a steep hillslope. *Adapted from:* Singh (1977a)

Construction of Hydraulic Ram

The hydraulic ram (Figs. 13.19 to 13.21) consists of an inclined supply pipe, called the drive pipe, connecting a supply channel at a higher elevation to a valve box located at a lower point. The valve box is provided with two automatic valves, a waste valve, also called impulse valve, opening inwards, and a delivery valve opening outwards. The delivery valve opens into an air chamber. A delivery pipe is taken from near the bottom of the air chamber. Gate valves are provided on the drive pipe and delivery pipe to control the flows. A strainer is provided at the intake of the drive pipe to prevent the entry of foreign material into it. By causing the waste valve to successively open and close, a dynamic pressure is created in the supply pipe which forces the water up the discharge valve. The discharge valve delivers water under pressure into an air vessel. From the air vessel, the water is delivered in a steady stream through the discharge pipe to the point of delivery which is at a much higher level than the supply channel.

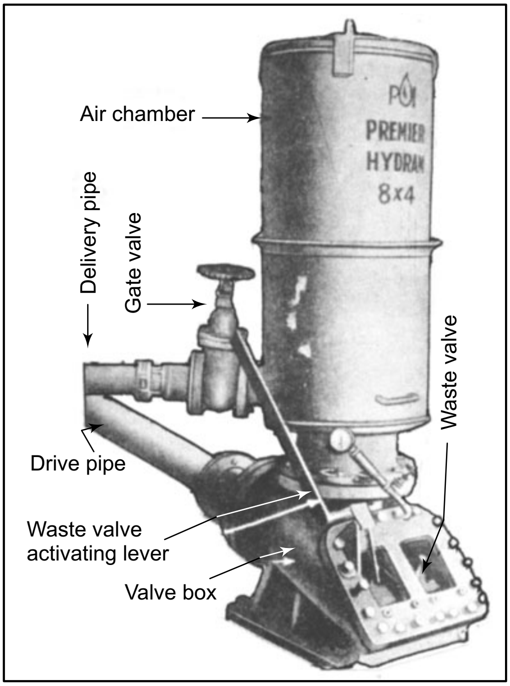


Fig. 13.19 A popular commercially available hydraulic ram of size 20 cm x 10 cm *Courtsy:* Premier Irrigation Co, Ltd., Kolkata

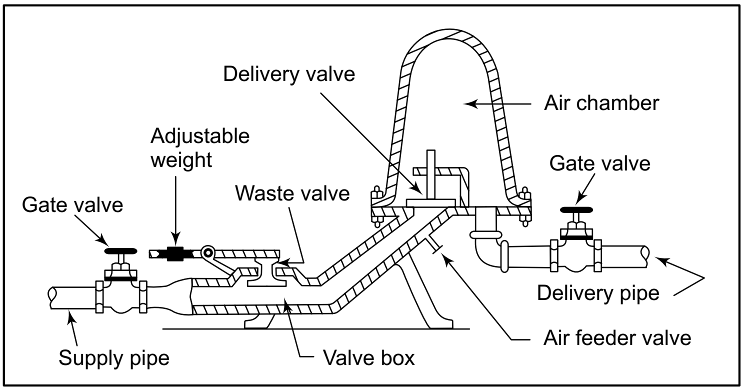


Fig 13.20 Sectional view of a hydraulic ram showing parts

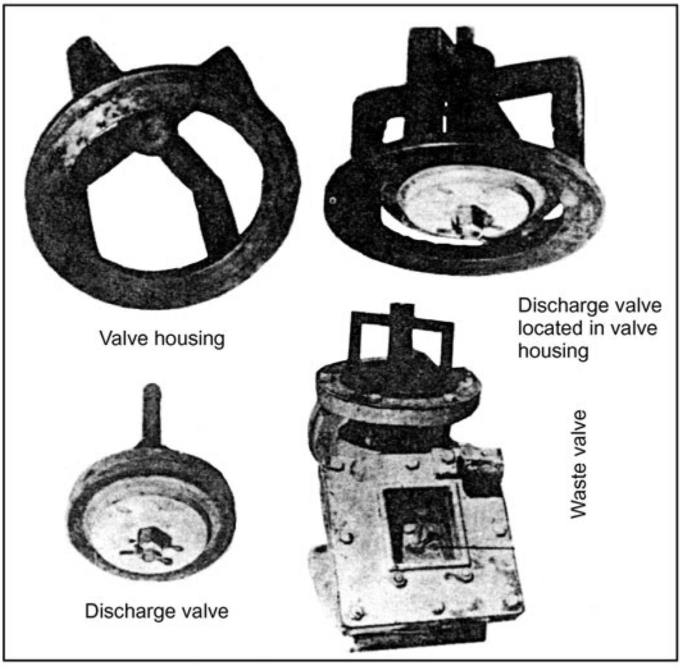


Fig. 13.21 Valve box and valves of a hydraulic ram

13.3.1 Principle of Operation

The hydraulic ram works on the principle of the *water hammer* (Figs. 13.22 and 13.23). The water hammer is a phenomenon resulting in an instant rise in pressure of the water flowing in a pipe, due to sudden stoppage of its motion. The cycle of operations in a hydraulic ram is as follows:

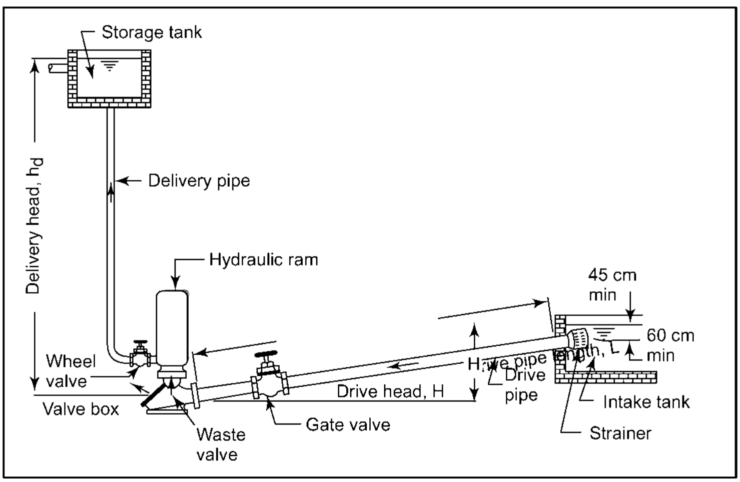


Fig. 13.22 Definition sketch illustrating the principle of operation of a hydraulic ram

The ram is started by opening the gate valve on the drive pipe. Water flows from the supply source, through the drive pipe, to the waste valve. The waste valve being open, water is free to escape and flow is set up along the drive pipe. The velocity of flow is increased under the influence of the supply head, until the dynamic pressure on the side of the waste valve becomes sufficiently great to overcome its weight. The valve then closes rapidly. The supply column suffers a consequent retardation which gives rise to a rapid increase of pressure in the valve box. This opens the delivery valve into the air vessel, compresses the air in it and water escapes through the discharge pipe. As soon as the momentum of the supply column is spent, the compressed air and the water under pressure closes the delivery valve. A backward motion of water occurs in the intake chamber and drive pipe, causing a negative pressure in the valve chamber. The waste valve, which is hinged on a steep angle in the valve box, falls back due to the vacuum and its own mass and allows water to flow out. As the velocity of water in the drive pipe increases, the gate valve again closes suddenly and the cycle is repeated. The frequency of operation varies from 25 to 100 times a minute. It can be adjusted by moving an adjustable weight or other mechanism.

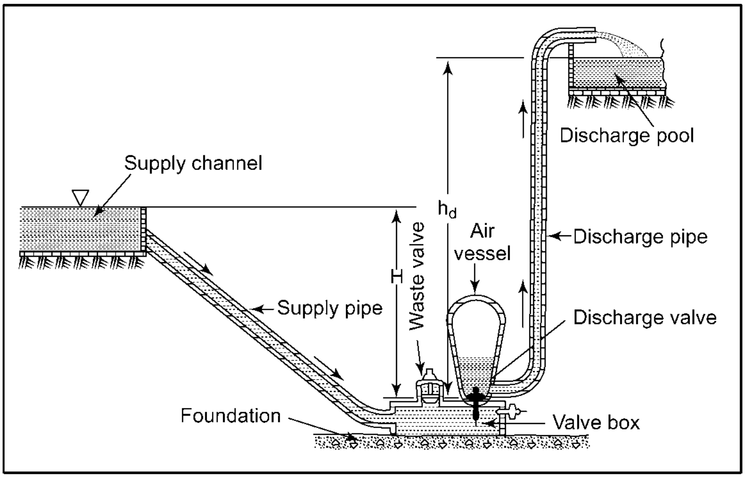


Fig. 13.23 Components and operating principle of a hydraulic ram

In order to develop maximum impulse, the supply pipe should be as long as possible. Installation of the ram too close to the source of water supply will reduce the impulse and, consequently, the delivery head. By introducing an air-feeder valve in the valve box, air is drawn into it when the pressure in the supply line falls below that of the atmosphere.

13.3.2 Advantages and Limitations

Advantages

1. The hydraulic ram is simple in construction and operation.
2. It does not incur any running cost, as it utilizes the energy of water available freely, and no fuel or electricity is required.
3. It has only two moving parts, the waste valve and the delivery valve, both of which are lubricated by the water itself. Thus, no separate arrangement for lubrication is required.

4. It ensures continuous water supply, as it operates throughout the day and night.
5. It works efficiently over a wide range of flows in the supply stream.
6. It does not cause any pollution.

The smaller sizes of hydraulic rams can be fabricated locally, using simple workshop equipment.

Limitations

1. For the installation of a hydraulic ram, a minimum fall of 1 m from the stream to the ram is required.
2. The hydraulic ram can lift only a small part of the flow which is fed to it (Generally it lifts about 1/20th to 1/10th of the water supplied through the drive pipe).
3. Since the ram works all 24 hours in a day, a storage tank is necessary to store the night supply.
4. Due to comparatively high initial investment, it is more adapted to ownership by small groups of farmers who can share the water amongst themselves, or by public agencies under rural water-supply schemes.

13.3.3 Efficiency of Hydraulic Rams

The efficiency of a hydraulic ram may be expressed in two ways. The first expression, known as D'Aubuisson's efficiency ratio, gives the efficiency of the ram as a machine. This is the ratio between the input energy of the ram and its output energy. The second expression, known as the Rankine formula for efficiency, considers the ram as a hydraulically operated pump. This takes into account the difference in elevation between the water surface in the supply channel and the delivery point as the actual delivery head.

Let q = volume of water lifted by the ram, m^3/s
Q = volume of water escaping through the waste valve, m^3/s
H = supply head (height of the source of water above waste valve), m
H_f = head loss due to friction in supply pipe, m
h_d = delivery head (elevation of discharge point above waste valve), m
h_{d_f} = head loss due to friction in delivery pipe, m

(i) D'Aubuisson's Efficiency Ratio

$$\frac{qh_d}{(Q+q)H} \tag{13.10}$$

A more precise expression of the efficiency of the ram, taking into account the head loss due to friction in the supply and delivery pipes is

$$\frac{q(h_d + h_{d_f})}{(Q+q)\,(H - H_f)} \tag{13.11}$$

(ii) Rankine's Formula for Efficiency

$$\frac{q(h_d - H)}{Q\,H} \tag{13.12}$$

EXAMPLE 13.5 A hydraulic ram operates at a drive head of 3 m and a delivery head of 20 m. The flow through the drive pipe is 10 l/s and the discharge at the outlet of the delivery pipe is 1.2 l/s. Compute the efficiency of the ram adopting (i) D' Aubuisson's ratio, and (ii) Rankine's formula.

Solution

Given, $H = 3$ m; $h_d = 20$ m; $Q + q = 10$ l/s;
$Q = 10 - 1.2 = 8.8$ l/s

(i) D' Aubuisson's efficiency ratio $= \dfrac{q\, h_d}{(Q + q)\, H}$

$$= \frac{1.2 \times 20}{(8.8 + 1.2)3} = 0.8$$

Efficiency value, % = 0.8 × 100 = 80.00

(ii) Rankine's formula,

$$\text{Efficiency, \%} = \frac{q(h_d - H)}{Q\, H} \times 100$$

$$= \frac{1.2\,(20 - 3)}{8.8 \times 3} \times 100$$

$$= 77.27$$

It may be seen that Rankine's formula gives a lower efficiency for the ram, compared to D' Aubuisson's ratio.

Improving the Efficiency of Hydraulic Rams

The main causes of energy loss in hydraulic rams are (i) friction and other losses in the supply pipe and valves, and (ii) velocity energy lost in the water leaving the waste valve. In a hydraulic ram with known values of supply and delivery heads, both (i) and (ii) vary approximately as the square of the mean velocity of water in the supply pipe. The energy input, on the other hand, varies directly as the mean velocity. Hence, it is possible to improve the efficiency of the machine by reducing the mean velocity of water in the supply pipe. This can be done by reducing the lift of the waste valve. This modification, by limiting the maximum supply pipe velocity, diminishes the mean velocity as desired.

13.3.4 Design Considerations for Installations

The design requirements of a hydraulic ram and its installation depend on the choice of the appropriate *lift magnification factor*, length and diameter of the supply pipe, design of the waste valve and air chamber, and size of the delivery pipe.

Lift Magnification Factor

The ratio between the delivery head and the supply head is called the lift magnification ratio or the magnification factor, i.e.

Lift magnification factor = h_d/H

The efficiency of a hydraulic ram varies almost inversely as the magnification factor. Most hydraulic rams work at the best efficiency (66 to 70%) if the lift magnification ratio is limited to 3 : 1 to 4 : 1. At a lift magnification ratio of 8 : 1, 12 : 1 and 24 : 1, the commonly obtained efficiencies of the ram are 52%, 37% and 4%, respectively. Normally, hydraulic rams are not applied for lifts exceeding 20 times the drive head. In general, the height to which water can be lifted by a hydraulic ram is about 100 m. The efficiencies, obviously, will depend on the design of the hydraulic ram, the length of the supply and delivery pipes and their materials of construction, and the number and types of pipeline accessories used in the installation.

Example 13.6 Estimate the discharge of a hydraulic ram to be installed in a rural water supply system, under the following conditions:

(i) Flow through drive pipe = 10 l/s
(ii) Drive head = 4.7 m
(iii) Delivery head = 18.8 m
(iv) Diameter of drive pipe = 10 cm
(v) Length of drive pipe = 34 m
(vi) Diameter of delivery pipe = 5 cm
(vii) Length of delivery pipe = 25 m
(viii) Accessories
  (a) Gate valve in drive pipe, 1
  (b) Gate valve in delivery pipeline, 1
  (c) Number of bends, 3

Galvanized iron pipes and fittings are used in the installation. The efficiency of the ram for a lift magnification factor of 4 : 1 (equivalent to 18.8: 4.7) as given in manufacturer's catalogues, is 62%.

Solution

Darcy's formula,

$$h_f = \frac{4\, f\, lv^2}{2\, g\, d}$$

is used in estimating the head loss due to friction in the pipes. The coefficient of friction is assumed to be 0.005.

Area of cross-section of drive pipe $= \frac{\pi}{4}\, d^2$

$$a_1 = \frac{\pi}{4}\left(\frac{10}{100}\right)^2 = 0.00786 \text{ m}^2$$

$\therefore$ Velocity of flow through drive pipe, $V = \dfrac{Q}{a_1} = \dfrac{10}{1000 \times 0.00786}$

$$= 1.27 \text{ m/s}$$

Acceleration due to gravity, $g = 9.81$ m/s^2

Head loss due to friction in drive pipe

$$= \frac{4 \times .005 \times 34 \times 1.27^2}{2 \times 9.81 \times 10/100}$$

$$= 0.56 \text{ m}$$

Assuming an efficiency of 62% for the ram, as provided in the manufacturers catalogue, the approximate discharge of the ram is computed, using Rankine's efficiency formula, as follows:

$$\text{Efficiency} = \frac{q\,(h_d - H)}{QH}$$

$$0.62 = \frac{q\,(18.8 - 4.7)}{10 \times 4.7}$$

$$\therefore \qquad q = \frac{0.62 \times 10 \times 4.7}{18.8 - 4.7} = 2.07 \text{ l/s}$$

$$\text{Area of cross-section of delivery pipe, } a_2 = \frac{\pi}{4}\left(\frac{5}{100}\right)^2 = 0.002 \text{ m}^2$$

$$\text{Velocity of flow in the delivery pipe} = \frac{q}{a_2} = \frac{2.07}{1000 \times 0.002}$$

$$= 1.035 \text{ m/s}$$

Head loss due to friction in delivery pipe

$$= \frac{4 \times 0.005 \times 25 \times (1.035)^2}{2 \times 9.81 \times 5/100}$$

$$= 0.55 \text{ m}$$

Head losses in pipeline accessories are obtained from Table 9.1 and the nomographic solution given in Fig. 9.12, Chap. 9 and are as follows:

(a) 10 cm gate valve in drive pipe = 0.025 m
(b) 5 cm gate valve in delivery pipe = 0.016 m
(c) Three 5 cm bends in delivery pipe = 0.034 × 3 = 0.102 m

$$\therefore \qquad H_f = 0.56 + 0.025 = 0.585 \text{ m}$$

$$h_{d_f} = 0.55 + 0.016 + 0.102 = 0.668 \text{ m}$$

Applying Eq. 13.11,

$$\text{Efficiency} = \frac{q\,(h_d + h_{df})}{(Q + q)\,(H - H_f)}$$

$$0.62 = \frac{q\,(18.8 + 0.668)}{(10 + q)\,(4.7 - 0.585)}$$

$$\therefore \quad 0.62\ (10 + q)\ (4.115) = 19.468\ q$$

$$25.513 + 2.5513\ q = 19.468\ q$$

$$16.917\ q = 25.513$$

$$\therefore \quad q = 1.51\ \text{l/s}$$

Size of Drive Pipe

The size of the drive pipe is so designed that the rate of flow of water through it is at least three times the rate of discharge through the delivery pipe. The approximate size of the drive pipe may be computed from the following relationship:

$$D = \sqrt{0.5\,(Q + H)} \tag{13.13}$$

where, D = diameter of the supply pipe, m

Q and H are as defined in Sec. 13.3.3

The range in values of the length of the supply pipe is estimated from the following relationship:

$$L = 1.5\ (h_d - H) \text{ to } 3\ (h_d - H) \tag{13.14}$$

The OISCA Hydram Company (Singh, 1977a) has recommended a slope of 7° for the supply pipe, which is obtained by laying the pipe at a gradient of about 8 : 1. Anon. (1969) has recommended that the ratio of vertical fall to the length of the drive pipe should be 1 : 6 when the fall is upto 4.5 m, 1 : 4 when the fall is 7.5 m, and 1 : 3 when the fall is 15 m. A thumb rule commonly used is to keep the ratio of diameter to the length of drive pipe as 1 : 500. Longer drive pipes do not increase the efficiency of the ram substantially, but permit the pump to operate at less strokes per minute, which results in less wear to the valve and longer operating life.

Heavy galvanized pipes with leak-proof joints are essential for the drive pipe as it has to withstand high pressure due to water hammering. The drive pipe should be straight, as far as possible, and without any elbows. Generally, the size of the drive pipe and that of the intake of the ram are kept the same.

Delivery Pipe

The discharge of the hydraulic ram is inversely proportional to the delivery head. The discharge pipe may have a uniform size if the water is tapped only at the highest point. If, however, the water is to be taken out at intermediate points, a variable-size delivery pipeline may be used. A larger size pipe is used in the lower section to reduce the head loss by friction and to obtain a higher rate of discharge. The pipe size may be reduced in steps at each point the flow is tapped. The size of the delivery pipeline is to match the magnification factor and the size of the supply pipe approximately, as follows:

Magnification factor	*Ratio of diameter of delivery pipe to supply pipe*
10	1 : 1
10-20	1 : 4
20-30	1 : 6
30-50	1 : 8

Medium quality galvanized iron, rigid PVC or high density polyethylene (HDPE) pipes may be used for the delivery pipeline. In case of polyethylene pipe, it is desirable to lay it underground to ensure durability. Bursting of the delivery pipe due to poor quality is a common cause of failure of hydraulic ram installations. Adequate pressure rating of the pipe should be insisted on while purchasing the pipe. BIS standards are a good guideline in selecting HDPE, PVC or GI pipes. In high-head installations, it may be advantageous to have the lower 1/3rd or half length of the pipeline of GI, and the rest of HDPE, in view of the ability of the GI pipe to withstand high pressure.

If the delivery pipe has any high points or abrupt turns where air might get trapped, an air valve or air vent is necessary. A threaded brass screw fitted to the HDPE pipe is often sufficient, if it is used with care.

Waste Valve

The dynamic pressure on the waste valve is given by the following relationship:

$$P = k\,\frac{wv^2}{2g} \tag{13.15}$$

where P = dynamic pressure, kg/m^2

w = specific weight of water, kg/m^3

v = velocity of water past the waste value, m/s

The value of the coefficient k is usually assumed to be 0.6 (Lal, 1969).
Therefore, the velocity of water past the waste valve is

$$v = \sqrt{\frac{P2\,g}{k\,w}} \tag{13.16}$$

The maximum velocity of water in the supply pipe is determined from the following relationship:

$$v_m = v \times \frac{\text{Effective area past waste valve when fully open}}{\text{Area of supply pipe}}$$

In practice, the waste valve is made to weigh 21 to 28 g/cm^2 of the valve area, so that a static pressure, corresponding to a 30 cm head, would be sufficient to prevent any opening (Gibson, 1934).

The period of time during which the waste valve is fully open depends on the time necessary to produce the required velocity of flow along the supply pipe. It will, therefore, increase with the weight of the valve and the ratio of the length of supply pipe to supply head.

The time required for the waste valve to close depends on the shape of valve body and the valve box. It will increase with increase in lift and weight of the valve.

The total time during which the waste valve remains off its seat will increase with the delivery head and the length of the supply pipe. It will also increase with the weight and lift to the valve. On the other hand, the time during which the waste valve is on its seat increases with the distance from the valve seat to the air chamber. The faster the valve reaches its seat after once beginning to close, the less will be the consequent loss of energy in the waste water.

The number of beats per minute of the waste valve depends on the time taken for the maximum velocity (v_m) to build up in the supply pipe and the time for which the delivery valve remains open. Thus,

$$T = T_1 + T_2 \tag{13.17}$$

where, T = time taken for one beat of the waste valve, s

T_1 = time for which the delivery valve remains open, s

T_2 = time to build up velocity v_m in the supply pipe, s

T_1 and T_2 may be estimated as follows:

(i)
$$T_1 = \frac{l \times v_m}{g\,(h - H)} \tag{13.18}$$

where, l = length of the supply pipe, m

g = acceleration due to gravity, m/s^2

(ii)
$$T_2 = \frac{(h - H)}{H} \times T_1 \tag{13.19}$$

The discharge of a hydraulic ram is influenced by the number of beats per minute and the weight of the waste valve. Studies at G.B. Pant Agricultural University have shown that the efficiency of a hydraulic ram decreased from 83.83 per cent to 76.78 per cent with an increase of number of the beats from 21 to 29 at 42 m head. It was also observed that the decrease in efficiency was higher at lower operating heads. Studies at Pantnagar have also shown that the delivery discharge and efficiency of hydraulic rams increased with the increase in the weight of the waste valve, within certain limits. Gibson (1934) recommended that the weight of the waste valve should usually range from 0.021 to 0.0316 kg/cm^2 of its base area. Studies at Pantnagar, however, showed that in a 15 cm × 7.5 cm size hydraulic ram, the maximum weight which gave the best performance was 0.056 kg/cm^2 of its area. (In case of a 10 cm × 5 cm size hydraulic ram, however, the maximum weight which gave the best performance was 0.023 kg/cm^2 of its area as against 0.17 kg/cm^2 which was the original weight). Studies at Pantnagar further showed that in case of the weight of delivery valve, increasing the weight reduced the discharge within the limits of practical application. For example, increasing the weight from 1.808 kg to 2.033 kg and 2.368 kg decreased the discharge of the ram from 1.63 lit/sec to 1.53 lit/sec and 1.47 lit/sec respectively.

The performance of a hydraulic ram, in terms of the quantity of water fed through the supply pipe and the quantity raised through the delivery pipe, varies greatly, depending on the factors discussed above. The discharge per beat of the waste valve is a function of various factors. The total discharge in unit time is the product of the discharge per beat and the number of beats during the period.

The lowest head for the operation of the ram is about 60 cm. The delivery head should, as far as possible, be within 6 to 12 times the supply head. The quantity of water delivered by the ram is about 1/10th to 1/20th of the amount supplied, depending on the magnification factor. An approximate estimate of the quantity of water raised by a hydraulic ram may be obtained from the following formula:

$$q = \frac{HQ}{2h_d} \tag{13.20}$$

Example 13.7 A hydraulic ram, working on a supply head of 3 m and a delivery head 10 m, gave a discharge of 2.5 l/s. The rate of flow through the waste valve was 20 l/s. The diameters and length of the supply and delivery pipes were 10 cm and 5 cm and 7.5 m and 18 m, respectively. Assuming a value of 0.01 for the coefficient of friction in the pipe, determine the efficiency of the ram.

Solution

Given,
$$Q = 20 \text{ l/s}$$
$$= 0.02 \text{ m}^3\text{/s}$$
$$q = 2.5 \text{ l/s}$$
$$= 0.0025 \text{ m}^3\text{/s}$$
$$H = 3 \text{ m}$$
$$h_d = 10 \text{ m}$$

Area of cross-section of supply pipe,

$$a_1 = \frac{\pi}{4}\left(\frac{10}{100}\right)^2$$
$$= 0.007857 \text{ m}^2$$

Area of cross-section of delivery pipe,

$$a_2 = \frac{\pi}{4}\left(\frac{5}{100}\right)^2$$
$$= 0.001966 \text{ m}^2$$

Velocity of water in the supply pipe,

$$= \frac{(Q+q)}{a_1}$$
$$= \frac{0.02 + 0.0025}{0.007857}$$
$$= 2.861 \text{ m/s}$$

Velocity of water in the delivery pipe,

$$= \frac{q}{a^2} = \frac{0.0025}{0.001966}$$
$$= 1.272 \text{ m/s}$$

Apply Darcy's equation for the head loss in the pipes,

$$H_f = \frac{4flv^2}{2gd}$$
$$= \frac{4 \times 0.01 \times 7.5\,(2.861)^2 \times 100}{2 \times 9.81 \times 10}$$
$$= 1.251 \text{ m}$$
$$h_{d_f} = \frac{4 \times 0.01 \times 18 \times (1.272)^2 \times 100}{2 \times 9.81 \times 5}$$

Efficiency of the ram (Eq. 13.11)

$$= \frac{q(h_d + h_{df})}{(Q+q)(H - H_f)}$$

$$= \frac{0.0025\,(10 + 1.1875)}{(0.02 + 0.0025)\,(3.0 - 1.251)}$$

$$= 0.7107$$

$$= 71.07\%$$

EXAMPLE 13.8 Determine the weight of a waste valve of diameter 10 cm, for a hydraulic ram. The valve is to start closing when the velocity of flow through it is 1.8 m/s.

Solution

Area of the base of the waste valve

$$= \frac{\pi}{4}\left(\frac{10}{100}\right)^2 = 0.007857 \text{ m}^2$$

Also, $v = 1.8$ m/s

and $w = 1000$ kg/m^3

Dynamic pressure on the valve

$$= k\frac{wv^2}{2g}$$

$$= \frac{0.6 \times 1000 \times (1.8)^2}{2 \times 9.81}$$

$$= 99.08 \text{ kg/m}^2$$

∴ The weight of the valve = pressure at the base

$$= 99.08 \times 0.007857$$

$$= 0.778 \text{ kg}$$

EXAMPLE 13.9 The waste valve of a hydraulic ram is 10 cm in diameter and weighs 1.6 kg. The valve travel distance is 6 mm. The supply pipe is 10 cm in diameter and 10 m long. The number of beats of the valve is 120 per minute. Determine the discharge rate of the ram against a delivery head of 8 m.

Solution

Pressure required to close the waste valve (Dynamic pressure on waste valve),

$$P = \frac{1.6}{\frac{\pi}{4} \times \left(\frac{10}{100}\right)^2}$$

$$= 203.82 \text{ kg/m}^2$$

$$= k \frac{wv^2}{2g}$$

∴ Velocity of water past the waste valve

$$= \sqrt{\frac{2gP}{kw}}$$

$$= \sqrt{\frac{2 \times 9.81 \times 203.82}{0.6 \times 1000}}$$

$$= 2.582 \text{ m/s}$$

Now, $$v_m = v \times \frac{\text{Area past waste valve when fully open}}{\text{Area of supply pipe}}$$

$$\text{Area past waste valve} = \text{Circumference} \times \text{Lift} = \pi d \times \text{Lift}$$

$$= \pi \times \left(\frac{10}{100}\right) \times \frac{6}{1000}$$

$$= 0.00188 \text{ m}^2$$

$$\text{Area of supply pipe, } a_s = \frac{\pi}{4}\left(\frac{10}{100}\right)^2 = 0.007857 \text{ m}^2$$

$$v_m = 2.582 \times \frac{0.00188}{0.007857}$$

$$= 0.6178 \text{ m/s}$$

Kinetic energy of the column of water in the supply pipeline at the time of closing the valve

$$= \frac{1}{2} m v_m^2 = \frac{w a_s L}{2g} v^2$$

$$= \frac{1000 \times 0.007857 \times 10 \times (0.6178)^2}{2 \times 9.81}$$

$$= 1.528 \text{ kg m}$$

∴ The weight of water that could be lifted per beat against the delivery head of 8 m $= \frac{1.528}{8}$

$$= 0.191 \text{ kg}$$

∴ The discharge, $q = 120 \times 0.191$

$$= 22.92 \text{ kg/min}$$

$$\approx 231/\text{min}$$

13.3.5 Installation, Operation and Maintenance of Hydraulic Rams

The selection of a suitable site, careful planning of the various components of the system, and adherence to correct procedures in installation and maintenance, contribute substantially to the economics and efficiency of a hydraulic ram.

Criteria for Selection of Site for Hydraulic Ram Installation

The following points are to be taken into account while selecting the site for installing a hydraulic ram for irrigation/water supply:

1. Quantity of water available in the stream during the cropping seasons and lean periods of flow
2. Available fall in the stream (supply head)
3. Elevations of the water supply points in the area proposed to be brought under irrigation and/or the elevation of the water storage tank
4. Distance of the ultimate delivery point of water from the proposed site of the hydraulic ram
5. Safe distance from the path of possible landslides and avalanches in snow-bound areas
6. Possibility of stable foundation for the ram, intake tank and a stable bed for the drive pipe
7. Total area proposed to be brought under irrigation/proposed population to be served and the ancillary requirement of the community
8. Existing and proposed cropping patterns of the area to be irrigated
9. Estimated requirement of irrigation water
10. Expected rainfall in terms of amount and periods of occurrence (to estimate the shut-off periods in case the ram is used exclusively for irrigation)

Location of the Hydraulic Ram

The location of the hydraulic ram is so selected as to have a minimum length of supply channel and pipeline. Adequate investigations at the site will help determine a location having the maximum possible vertical fall with the minimum length of supply channel. The supply channel is a costly item in the installation of the ram, and should be as short as possible. As a general rule, the ram should be located as close as possible to the source of supply and the delivery point, while maintaining the highest possible vertical fall. Often, it may be desirable to sink a deep ram pit and dig out for the drive pipe and waste-flow line, thus obtaining a greater vertical fall, to lift a larger quantity of water.

In a typical hydraulic ram installation, a supply head is created by digging a small contour diversion channel along the bank of a river or stream. In case of small streams, it is a common practice to construct a weir and install the hydraulic ram directly below it. Where greater capacities are required, it is possible to install several hydraulic rams in parallel with their discharge pipes joining a common main delivery pipe.

It is desirable to lay the delivery pipe on the shortest possible route to economise on the cost of the pipe and reduces the head loss due to friction. Sharp bends should be avoided in the pipeline. Hydrants are to be provided in the delivery pipeline, at different levels, to irrigate fields with the minimum pumping head. The size of the hydraulic ram and the number of rams required at a site are determined on the basis of the flow which could be diverted from the stream, the magnification factor, and the requirement of water for the proposed cropping pattern/population to be served. In case of irrigation projects, when the available water is limited, the cropping pattern could be varied to use the available water most efficiently.

The size of the hydraulic ram is designed on the basis of the diameter of the supply pipe and the delivery pipe. The sizes of hydraulic rams commercially available in India are 10 cm × 5 cm and 30 cm × 15 cm. Larger size rams could be manufactured to meet specific requirements.

The selection of a specific make of hydraulic ram is made on the basis of the performance data provided by the manufacturer, the suitability to the site, the availability of spares, and technical support. The procedure for selecting pumping sets, described in Ch. 9 apply to hydraulic rams as well. The size of the ram is determined by the output desired, or limited by the supply of water available to drive the ram. All other factors remaining same, a ram which gives the highest efficiency is selected for installation.

Example 13.10 Assuming the following conditions, estimate the minimum expected flow rate of the source of water, for installing a hydraulic ram in a rural water supply scheme:

Vertical fall	= 9 m
Vertical lift	= 60 m
Population of village	= 200
Rate of increase of population	= 25% in 15 years
Water allowance	= 45 l/day/person
Efficiency of ram	= 60%

Solution

Estimated population in 15 years at 25% increase

$$= 200 + \frac{25}{100} \times 200 = 250$$

$$\text{Water demand} = 250 \times 45 = 11{,}250 \text{ l/day}$$

Using Eq. (13.12) (Rankine's formula),

$$\text{Efficiency} = \frac{q(h_d - H)}{QH}$$

or

$$Q = \frac{q\,(h_d - H)}{\text{Eff.} \times H}$$

$$= \frac{11{,}250\,(60-9)}{0.6 \times 9}$$

$$= 106250 \text{ l/day}$$

$$= \frac{106250}{24 \times 60 \times 60}$$

$$\therefore \quad = 1.23 \text{ l/s}$$

Note In case the minimum rate of flow of source of supply is lower, it is still possible to get the desired output of water at the delivery, by increasing the vertical fall or reducing the vertical lift, by resorting to alternate locations and alignment.

Foundations for Hydraulic Rams

A reinforced concrete slab or a large flat rock provides a good solid foundation on which a hydraulic ram could be installed (Fig. 13.24). The foundation should be made of 1 : 2 : 4 cement concrete and should be large enough to protect the hydraulic ram from vibrations. The depth of the foundation can range from 0.8 to 1.2 metres, depending on the weight of the ram and the type of soil (Fig. 13.24). For hydraulic rams of sizes exceeding 10 cm × 5 cm and for delivery heads exceeding 30 m, the foundation should preferably be made of reinforced concrete. It is a good practice to use a mild-steel base plate to locate the ram. Foundation bolts of length 30 to 45 cm and 1.5 to 2 cm diameter are used on all four corners. It is desirable to provide a rubber or felt packing under the ram to avoid migration of the vibration into the foundations. It is good to enclose the ram in a concrete/masonry pit.

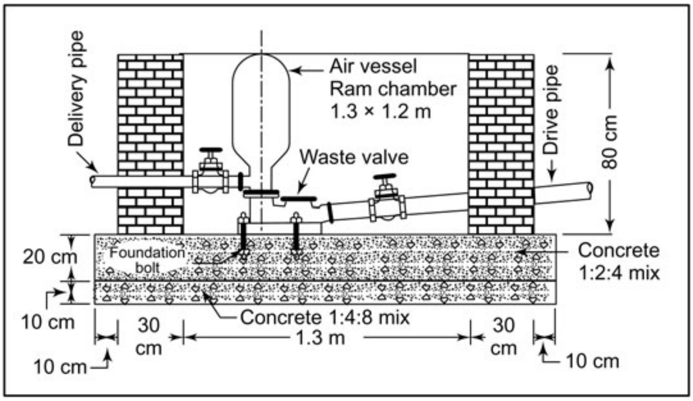


Fig. 13.24 Details of installation of a hydraulic ram

The ram pit should be large enough to provide a clearance of about 45 cm from the ram, on all sides, in order to facilitate the dismantling of the ram when required. The walls of the pit should be high enough to prevent flood water entering it. A sloping roof of corrugated iron or asbestos cement sheets provides a satisfactory roof for the ram house. In cold climates, it is desirable to cover the house with a concrete slab in order to prevent freezing. A man-hole cover (usually cast iron lid) can be used to provide an opening to enter the ram pit. This cover can be provided with a lock, if desired.

Use of Hydraulic Rams in a Battery

It may often be advantageous to install two or more hydraulic rams in a battery, utilizing a common diversion point, supply channel and intake tank. However, each ram should have its own individual drive pipe, but a common delivery pipe is sufficient to carry the water pumped by the individual rams (Fig. 13.25). Studies at the State Planning Institute, Lucknow, have shown a 30 per cent reduction in the cost of irrigation development when a battery of two rams is used at one station. A battery of rams has the advantage of using more rams during periods of high flow in the stream, and reducing the number during the dry seasons when the flow reduces. It is often sufficient to use a common delivery pipe of larger size in the lower section of the line and provide separate hydrants to feed the fields at the lower levels. It is also possible to install a series of hydraulic rams (Fig. 13.26) in a system. In such an installation, the source of supply of the lower ram is the waste flow of the ram immediately above it. In series installations, it is possible to have a common water-storage tank or separate ones for each ram, depending on local requirements.

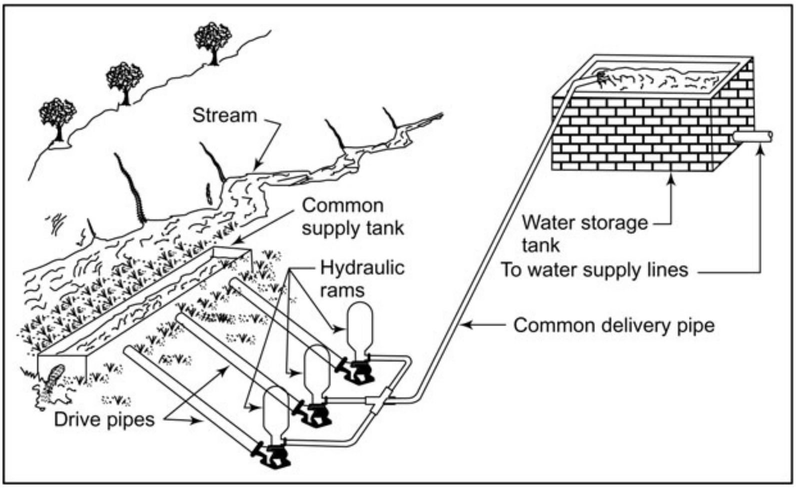


Fig. 13.25 Installation of a series of hydraulic rams in parallel

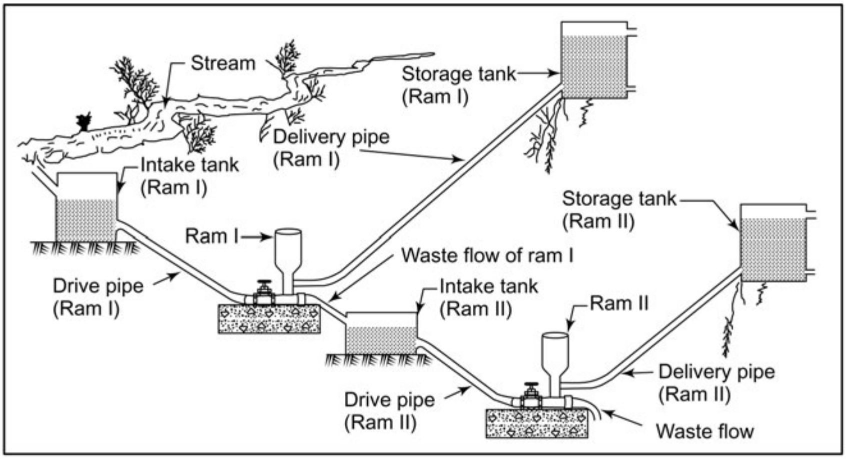


Fig 13.26 Hydraulic rams in series. The lower ram is powered by the waste water of the upper ram. The delivery pipes of the two rams may be independent as shown in the figure. Alternatively, the delivery pipe of Ram II may be joined to that of Ram I at a suitable point along the line. Similarly, the storage tank may be independent or common, depending on the requirements

Conjunctive use of Conventional Pumping Sets and Hydraulic Rams

In many situations, pumps operated by electric motors and diesel engines are often more economical than hydraulic rams, when low and medium lifts are involved. However, they become uneconomical when used for low-discharge and high-head situations. In such cases, it may be advantageous to use a conventional pumping set in conjunction with a hydraulic ram. The discharge of the pump is fed into a supply tank feeding a hydraulic ram located at an intermediate elevation on the hill slope. The hydraulic ram raises a part of the pump discharge to irrigate the higher reaches. The flow escaping through the waste valve of the ram, being the major portion, is fed through a channel or pipes to irrigate the area below.

Ancillary Structures

Certain ancillary structures are essential for the efficient functioning of a hydraulic ram. They include diversion work at the stream, supply channel, feeding tank and water storage tank (Fig. 13.15).

Diversion Structure

A diversion structure is usually required to raise the level of water in the stream and divert it to the supply channel feeding the hydraulic ram. These may be simple temporary dams or regular masonry weirs or dams. In many places, temporary walls formed by laying large stones may be adequate. Small boulder dams, with woven wire netting as envelop may often be suitable. The type of dam or weir will depend on the site conditions. Costly constructions are usually avoided in a small scale irrigation project like the installation of hydraulic rams.

Supply Channel

The supply channel leads the water diverted from the stream or rivulet to the intake tank. It is often necessary to provide a grating of iron rods/bamboo pieces/logs at the mouth of the supply channel to keep away floating matter carried by the stream. A major factor in determining the cost of a hydraulic ram installation lies in selecting the ram site, with a view to have the minimum length of the supply channel. The cost of the channel is almost directly proportional to its length. The size of the channel will depend on the quantity of water to be conveyed. Manning's formula is used to design the channel cross-section. Normally, a rectangular cross-section is preferred for the supply channel, as compared to a trapezoidal section. This will reduce the land occupied by the channel and also make the channel sides almost independent of the supporting earth ridge on either side.

Depending on the local conditions, the supply channel may be an unlined earth channel or lined channel. Any of the conventional lining materials—brick or stone laid in cement or lime mortar, or cement concrete, may be used for lining the supply channel. The choice would depend on their availability locally and comparative costs. Efforts should be made to adopt locally available materials, especially rubble stone, to line the supply channel. Earth channels may be trapezoidal or parabolic in cross-section. A rectangular cross-section is preferred in lined channels, for discharge capacities not exceeding 100 l/s. Supply channels are run almost along the contour to obtain the maximum possible supply head at the intake. Appropriate retaining structures, including retaining walls and spurs, are provided to protect the channel wherever required. At places where the supply channel is to run along an erodible hill-slope, it may be economical to convey water through an underground pipeline.

It is possible to increase the vertical fall (drive head) of ram by taking a contour channel or intake pipe from the diversion point at the stream to another point downstream where there would be a bigger drop to the pump. Too long a channel or pipeline will, however, increase the cost of the installation greatly. An open-stand pipe or an intermediate tank is provided at the junction between the intake channel or pipe and the drive pipe. The function of the structure is to ensure that there is no air in the drive pipe. The use of the open stand pipe is primarily for installations where the intake tank and the ram location are limited by the surrounding topography, or make it unnecessarily long or not steep enough. By using an open-stand pipe, the length and angle of the drive pipe will be determined by the stand-pipe location. The elevation of the top of the stand-pipe should be above the hydraulic grade line.

Intake Tank

A masonry intake tank is constructed at the intake of the drive pipe (Fig. 13.22). It is also known as a supply tank, feeding tank or filtration tank. The intake tank must be strong enough to withstand the vibrations of the hydraulic ram due to water hammering. The size of intake tank commonly used for small-scale installations is about 2 m long, 1.2 m wide and 1.2 m deep. A water depth of about 40 to 60 cm is provided over the mouth of the drive pipe to avoid whirlpools forming and sucking air into the drive pipe.

The inlet portion of the supply tank may be used for the separation of straw, leaves, etc. and to trap silt and sand carried through the supply channel. A wire mesh or expanded metal is fixed to the top section of the wall separating two sections of the tank, to hold back foreign material entering the supply pipe. Entry of foreign material is further checked by providing a bell mouth inlet with steel and wire mesh envelop at the inlet end of the drive pipe (Fig. 13.22).

Water Storage Tank

Irrigation in hilly regions is usually limited to the day time. Since the hydraulic ram works automatically throughout the day and night, without any expenditure on fuel or energy, it is desirable to store the night supply of water in a tank for use on the following day (Fig. 13.25). The minimum capacity of the tank is fixed to store about 12 hours' supply. Leak-proof masonry, mild steel or concrete tanks are required especially in water supply systems. The tank must have a wash-out pipe at the bottom, an inlet, service pipes for water supply and an overflow pipe near the top. The overflow should be taken to a pond for animals or fish or irrigation without causing any erosion problem. If the system is used only for irrigation, then a pond may often be sufficient. If the site conditions permit, the pond may be lined with low cost material like buried polyethylene film.

General Guidelines for Installing Hydraulic Rams

The following general guidelines are adhered to in the installation of a hydraulic ram:

(a) The hydraulic ram is installed level, on a steady and strong foundation.
(b) The ram is installed clearly away from the path of landslides and avalanches.
(c) The ram and pipes are protected from freezing temperature; which is a problem at elevations above 2400 m. When not in operation, the pump and pipe should be drained of water to prevent freezing temperatures from bursting the pipe.
(d) The drive pipe and delivery pipe should be connected to the hydraulic ram, preferably with a union joint and a gate valve. This will greatly facilitate servicing of the ram.
(e) All threaded joints should be wrapped with fine jute thread and then coated with a pipe sealant compound or enamel paints to prevent leaks in the joints.
(f) In cold climates, the pipes should be buried below the frost line.

Operating the Hydraulic Ram

Before starting the ram, leakages in the pipelines are checked and remedied. To start the ram, the gate valve on the delivery pipeline is closed and the valve on the supply pipe is opened fully. All the air bubbles are allowed to escape through the water passing the waste valve. The gate valve on the delivery side is then opened. It may be necessary to manually operate the waste valve for about 15 strokes, till it starts working automatically. A stick, pliers or tongs may be used for the purpose. The stem of the valve is not held by hand, to avoid injury due to the impact of water. The air feeder valve should be so set as to give a small spurt of water with each stroke. If the valve is opened too much, the air chamber will get filled with air and the ram will discontinue to lift water. On the other hand, if the ram is not sufficiently open, the water passing through it will absorb all the air in the air chamber and the ram will begin to pound with a metallic sound at every stroke. This situation should be promptly corrected by increasing the opening of the air feeder valve in order to avoid breakage of the parts of the ram.

The depth of the opening of the waste valve can be changed by suitable adjustments provided in the rams (Fig. 13.20). Increasing the opening of the waste valve reduces the number of its strokes and increases the amount of water the ram will use and deliver. Reducing the opening increases the number of strokes and decreases with quantity of water delivered.

Tuning of Hydraulic Ram

The number of beats of the waste valve may be adjusted to improve the performance of the ram. This process is called tuning. The performance of a hydraulic ram may sometimes be improved by reducing the number of beats of the waste valve. Higher delivery heads require lesser frequency of cycles of the valve. To operate the valve at maximum capacity, the waste valve is usually set to operate at 20 to 40 strokes per minute. To regulate the ram to operate at minimum capacity under normal conditions, the waste valve is set to operate at 60 to 100 strokes per minute. Larger size rams have slower maximum and minimum strokes. For reducing the frequency of cycles of the valve, weight is added to it, or the valve is adjusted by unscrewing the bolt holding it. Alternatively, in case of low- or medium-delivery heads, the weight on the valve is reduced or the bolt screwed in. Discharge measurements are taken while adjusting the impact valve to provide the correct setting.

Maintenance

The hydraulic ram is a simple machine with only two moving parts, namely, the waste valve and the delivery valve. It operates continuously for years, without much maintenance. The rubber thrust pads on the waste valve and the delivery valve may have to be changed once or twice a year. The ram and the pipelines have to be drained of water when the machine is not in operation during severe winter months, in order to prevent bursting of pipes due to freezing of water inside them. As long as the ram is working trouble-free, it is necessary to inspect it only once every 3 or 4 months in order to tighten the fittings, clean the ram of accumulated sediments, and check the valves for leakage and/or wear. Gate valves should be oiled twice a year and the ram and other exposed GI parts painted once a year. Screens and other parts, where sediments and other outside objects accumulate, should be inspected and serviced as required.

Trouble Shooting

The common troubles encountered in the operation of hydraulic rams, and their remedies, are given in Table 13.3.

13.3.6 On-farm Development for Irrigation with Hydraulic Ram

The initial cost of developing irrigation potential with a hydraulic ram is often high. The high cost of development of irrigation potential and the comparatively small discharges obtained with hydraulic

TABLE 13.3 Common Troubles in Hydraulic Ram Operation and their Remedies

Trouble	Remedy
1. Unusual noise from the hydraulic ram and intense vibration at the delivery pipe	There is no air in the chamber. Stop the ram, close the delivery valve and release water from the air chamber to introduce air in it. Ensure that there is no leakage of air at the air vessel joints before restarting.
2. Waste valve remains closed or open after repeated starting by hand	When the waste valve remains closed, the weight on it is less. In case it remains open, the weight on it is more. Adjust the weight accordingly. Also ensure that the valve hinge does not stick and there is no blockage of water through leaves and straw in the ram.
3. Waste valve works for a few strokes and then stops	There is air in the drive pipe. Evacuate the air by closing the waste valve for some time.
4. Ram works without any discharge of water	The seat of the delivery valve may be worn out and leaking. Replace the valve packing and recondition the seat. Ensure that the magnification factor does not exceed 50.
5. Ram lifts water with uneven strokes and fluttering sound	There may be an air pocket or leakage in the drive pipe. This can be removed by keeping the waste valve open for sometime with a lever to enable the water to escape or by sealing the pipe joints. There may be insufficient water above the mouth of the drive pipe. Sufficient submergence may be provided by constructing a small wall around the ram.

Adapted from: Machinery Dn., Mini. of Agr., Govt of India (1979).

rams call for efforts to economise on the use of water. This would require development of the command area, preferably in contour benches, for irrigation (Fig. 13.18). Use of lined channels and drop structures would save the water lifted at a high cost. Pre-fabricated concrete channel sections and simple low-cost chute spillways provided with check gates are suitable for water conveyance.

Amongst the surface methods of irrigation, contour furrows are most suitable in the hills. Hydraulic rams are ideally suited for use with low-pressure sprinkler and drip methods of irrigation. The pressure head in the storage tank at the delivery point is often sufficient to operate a conventional drip irrigation system or a low-head sprinkler system. Perforated spray-type sprinkers, being essentially low-pressure units, can be used with most hydraulic ram installations.

13.4 SOLAR PUMPS

Solar energy, with its virtually infinite potential and free availability, represents a non-polluting and inexhaustible energy source which can be developed to meet the energy needs of mankind in a major way. The high cost and reduced availability of fossil fuels and the public concern about the safety of nuclear reactors as a potential power source have led to a surge of interest in the utilization of solar energy. The sun gives an average energy input of 6 kW-h/day for each square metre of the surface of the earth it shines upon. The term standard solar day means that a collector surface receives 6 kW-h of energy per day per square metre to its surface. To evaluate the energy potential at a particular place, detailed information on its availability is essential. These include data on solar intensity, spectrum, incident angle and cloudiness as a function of time.

India receives a solar energy equivalent of 5000 trillion kW-h/year with a daily average solar energy incidence of 4-7 kW-h/m^2 surface area. This is considerably more than the total energy consumption of the country. Further, most part of the country experience 250-300 sunny days in a year, which makes solar energy a viable option in these areas.

Both the thermal and light parts of solar energy can be used as energy sources. The direct use of the thermal part of solar energy includes water heating, cooking, heating and cooling of buildings, drying of agricultural products and salt production by evaporation of sea water. Flat-plate thermal-energy collectors are used for domestic and agricultural applications. To obtain high temperatures, sunlight is concentrated on the collecting surface, using concentrators.

Water pumping by solar power is a concept which has won widespread interest since the early seventies. Solar energy can be utilized to operate pumps, utilizing either the thermal or light part of solar radiation.

Small scale irrigation is one of the most potential applications of solar power. The main advantage is that solar radiation is intense when the need for irrigation is high. Further, solar power is available at the point of use, making the farmer independent of fuel supplies or electrical transmission lines. The technical feasibility of solar (photovoltaic) pumps have been established. As late as 1988 the pump did not reach the stage of economic viability, especially in the medium and high head ranges, mainly because it was not being manufactured or extended on a large scale. The major limiting factor has been the high cost and the lack of familiarity of the technology which require concerted effort in training of technicians and large scale introduction in a region with adequate technical support.

13.4.1 Solar Thermal Pumps

The solar thermal pump consists of two main components, a collector, and an engine and pump unit. The thermal part of solar radiation is harnessed through suitable collectors. The collector is usually a parabolic trough panel with a smooth under surface. The panel is usually made as a sandwich laminate from two aluminium sheets, with an intermediate layer consisting of an aluminium honeycomb. A reflector film is applied to the parabolic inner surface of the collector on which the sun rays fall. The panel must be structurally strong to retain its parabolic shape.

The sunlight collected through the panel is concentrated on to an evaporation tube situated on the focus line. The tube contains a liquid of low boiling point, usually Freon 11, which vaporises and builds up pressure. The pump unit consists of a sealed power circuit with valves and cylinders. The gas under pressure operates the pump, which is usually of the double-acting piston type. The unit is usually provided with pressure control valves and automatic start and shut down. A few experimental prototype pumping systems have been developed using the above principle. Photovoltaic power systems, however, are preferred over thermal systems in operating pumps.

13.4.2 Photovoltaic Power Generation

Photovoltaic cells, frequently referred to as solar cells, convert the light part of the solar spectrum (sunlight) into electricity. They are the most rapidly expanding energy sources in the world. Cost reduction has been the main concern in solar cell manufacture in recent years. Large scale manufacture of photovoltaic cells, coupled with continued research and development, are expected to make photovoltaics within the economic framework of rural areas in developing countries.

Solar Cells

The solar cell operates on the principle of the photovoltaic effect—the creation of charge carrier within a material by the absorption of energy from the incident solar radiation. The solar cell is made of two thin layers of a semi-conductor material appropriately doped with impurity atoms so as to give one layer a negative electrical bias (*n*-bias) and the other a positive bias (*p*-bias). Sunlight falling on the cell reaches the junction between the two layers in the form of photons of energy, and knocks electrons across the junction. This results in the development of a potential difference across the two layers. Direct current (DC) electricity can be drawn across the two layers through an external circuit. The solar cell is not damaged by either a short-circuited or open-circuited load.

The efficiency of solar cells in converting incident solar energy into electrical energy depends on the illumination spectrum intensity, materials of construction and design of the cell, atmospheric temperature and dustiness of the sky. Dust-free atmosphere and low day temperatures lead to higher efficiency of solar cells. Silicon solar cells lose about 1/2 per cent efficiency for each 1 ºC rise in temperature above the standard day time temperature of 28 ºC. Efficiencies normally obtained range from 3 to 30 per cent. Solar cell used in running DC electric motors have efficiencies ranging from 6 to 12 per cent.

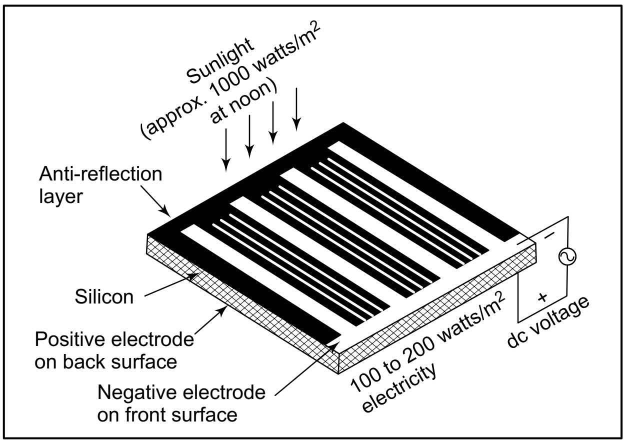


Fig. 13.27 Simplifed representation of a sillicon photovoltaic cell operation

Silicon is the most commonly used material for making solar cells (Fig. 13.27). Other materials include cadmium sulphide and gallium arsenide. The fabrication of the solar cell involves a large number of processes, starting from the growth and characterization of basic silicon material in water form, followed by junction formation, contact fabrication and anti-reflection coating on the active surface of the cell. The outer surface of the panel is protected by a special tempered glass which provides high transmittance of sunlight.

Solar Array

A solar cell behaves like a low voltage (0.5 volt) battery whose charge is continuously replenished at a rate proportional to the incident solar radiation. Connecting such cells into series-parallel configuration results in photovoltaic modules or solar arrays with high current and voltages. The power developed by a solar array ranges from 80 to 120 watts per square metre of the panel. The photovoltaic power can be utilized to operate conventional electrical appliances, including DC electric motors. The solar array is mounted on a simple frame which has provision for adjusting the array manually against the position of the sun. The angle of the array has to be changed about 3 or 4 times a day.

13.4.3 Adapting Pumps to Photovoltaic Power

The solar pump unit consists essentially of a solar array, a direct-current electric motor and a pumping unit. The other components are the electrical control and some mechanism for tracking the array against the sun. Two types of pumping sets are used with photovoltaic systems, a vertical centrifugal pump coupled to a submersible DC electric motor (Fig. 13.28), or an ordinary volute centrifugal pump close-coupled to a horizontal DC electric motor. However, the submersible pump unit is more suitable for the photovoltaic system. This arrangement eliminates the suction pipe and foot valve and results in a higher efficiency of the pumping unit. The submersible pump is made leak-proof by a silicon carbide mechanical seal. In case a volute pump is used, care is taken to limit the pump suction within about 4.5 m, to maintain a high level of pump efficiency.

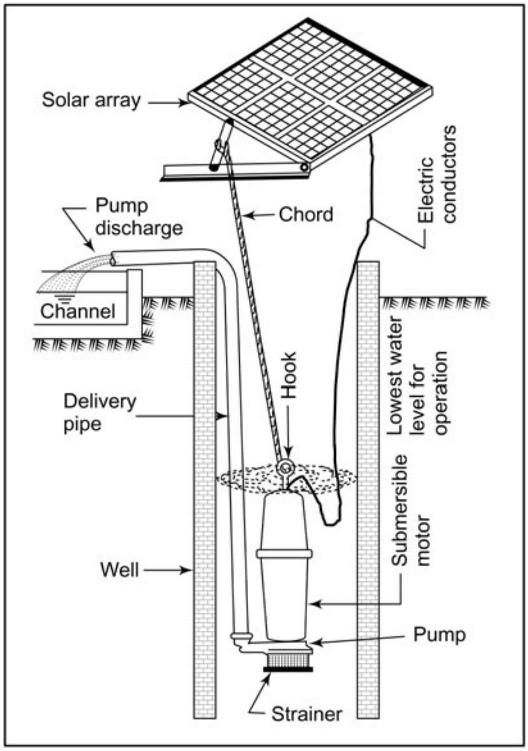


Fig. 13.28 Schematic sketch illustrating the installation of a photovoltaic pumping set using submersible motor and pump unit installed in a shallow open well

The output of the solar array varies with the intensity of the incoming radiation and other factors. Hence, it is necessary to match a variable-speed DC motor with the panel output. At least one make of photovoltaic-powered pumping sets utilizes a maximum power-control unit as an integral part of the system, in order to match the load on the pump to the varying power output of the panel.

There is considerable commercial interest in manufacturing photovoltaic-powered pumping sets. The power output of the system is directly proportional to the number of solar cells and the surface area of the panel exposed to the sun. The array has to be tracked 3 or 4 times daily to orient it to the sun. It requires shadow free area for installation of solar panel. The discharge of a solar pump from 1800 watts DC centrifugal pump varied from 6-8 l/s at a head of 5 m. This could irrigate about 1.5 to 2 ha of land with crops having moderate irrigation requirements.

13.4.4 Maintenance of Photovoltaic Systems

The solar panel is expected to provide about 20 years of satisfactory service under normal conditions, even though the cell itself may last much longer. The only maintenance requirement is occasional washing of the surface to maintain maximum optical transmission through the glass. If an individual cell of an array is damaged, the same can be replaced without disturbing the array. The panel has to be protected from breakage by external agencies. Some manufacturers cover the cell/array with unbreakable glass. The motor and the pump require the usual periodic maintenance like cleaning, lubrication and replacement of worn parts.

13.4.5 Advantages of Photovoltaic Pumping Systems

(i) *Cost Effective*

The life cycle and the cost to ultimate beneficiary makes this system cost effective as compared to conventional systems. In addition the farmer is saved from the capital investment he has to make for drawing lines from the grid to his field/farms. The government may save huge resources which otherwise may be uneconomical to network every agriculture field under the state electricity grid.

(ii) *Reliable*

This is more reliable, consistent and predictable power option as compared to conventional power system in rural areas.

(iii) *Free Fuel*

Sunlight, the fuel source of photovoltaic system is a widely available, inexhaustible, reliable and free energy source. Hence the SPV system has no monthly fuel bills.

(iv) *Low Maintenance*

The system operates on little servicing and no refueling, making them popular for remote rural areas, hence the operation and maintenance is very low. The suppliers provide maintenance at a very low annual maintenance contract rates.

(v) *Local Generation of Power*

The photovoltaic system make use of local resource-sunlight. This provides greater energy security and control of access to energy.

(vi) *Easy Transportation*

As photovoltaic systems are modular in nature they can easily be transported in pieces/components and are easily expandable to enhance the capacity.

(vii) *Energy Conservation*

Solar energy photovoltaic is clearly one of the most effective energy conservation programs and provides a means for decentralized photovoltaic-generated power in rural areas. Solar pump is energy efficient and a decentralized system.

(viii) *Water Conservation*

The photovoltaic sets are highly economical when combined with water conservation techniques such as drip irrigation and night time distribution of (day time pumped & stored) water. The SPV system leads to optimum exploitation of scarce ground water.

(ix) *Environmental Friendly*

The use of sunlight as a source of fuel leads to clean, eco-friendly and decentralised generation of energy which saves the fossil fuel, controls deforestation and prevents environmental pollution.

13.5 BIOGAS

The potential of biomass as an energy source is being increasingly realised. Biomass constitutes a significant, clean and renewable energy source. It is organic matter formed by plant and animals. Plant biomass is formed by the process of photosynthesis, by which plants are able to convert carbon dioxide and water into organic material and oxygen. It is estimated that plant photosynthesis fixed about 2×10^{11} tonnes of carbon with an energy content of 3×10^{21} joules, which is about 10 times the world's present annual energy consumption.

The biomass in the biological system may be classified in two broad categories: terrestrial biomass (organic residues and higher plants), and aquatic biomass (fresh-water aquatic plants, seaweeds, micro-algae and floating marine plants). Thus, the word biomass is a comprehensive term comprising all forms of matter, derived from biological activities and present either on the surface of the soil or at different depths of the vast body of waters—lakes, streams, rivers, seas and oceans.

Organic Residues

These are the renewable resources plentifully available in agro-processing centres (rice husk, groundnut shell, coconut shell, molasses, maize cobs, etc), farms (rice straw, jute sticks, cotton stalks, etc.), animal sheds (cattle dung and animal excreta), forests (bark, chips, shavings, sawdust), municipal wastes (city refuse, sewage), and industrial wastes (distillery effluents, etc.).

Energy Plants

Use of higher plants for energy production aims at raising only fast-growing short-duration species, to be used either directly as fuel or to be converted into substitutes for fossil fuels. A number of such plants have been identified/selected to be grown in the form of energy plantations (*Eucalyptus*, subabul, *Casuarina*), hydro-carbon plants (*Jajoba, Euphorbia, Asclepia*, babusa), dende, marmeleiro, and energy-cropping carbohydrate plants (sugarcane, sugarbeet, maize, sorghum).

The available processes for converting biomass either directly into heat or into gaseous, liquid or solid fuel includes both dry (non-biological) and wet (biological) processes. Burning of combustible materials in the open results not only in the dissipation of useful energy but also emission of particles and gases which results in atmospheric pollution. The development of efficient energy-conservation devices such as biogas plants, furnaces, heat exchangers, steam generators, stoves and heaters can help provide not only clean fuel with a minimum of smoke but also produce adequate energy to meet the needs of households and processing units in many areas.

13.5.1 Biogas Energy

Biogas is a mixture of gases containing methane, carbon dioxide, hydrogen and traces of a few other gases produced by the anaerobic fermentation of easily decomposible cellulosic materials. Animal manure (cattle dung) and municipal sewage have been the main materials used for producing biogas. The process has the advantage that animal and human waste can be used to generate energy while, at the same time, retaining their nutrient value for use as organic fertilizer. The production of methane gas from crop residues and aquatic plants like water hyacinth have also been attempted with considerable success. Water hyacinth is one of the major weeds leading to the blocking of many drainage canals and even irrigation canals. They also create serious problems by blocking tanks and other stagnant water bodies. Their removal and use as a source of energy provides not only a substantial energy source, but will simultaneously contribute to solve the problem of blocking of water bodies.

Biogas has been found to be a useful fuel in a number of developing countries. Several million biogas plants, community type and small units, are known to be operating in China and India.

13.5.2 Biogas Plants

Biogas plants may be classified into two, namely drum type and drumless type.

Drum-Type Biogas Plants

The conventional biogas plant, originally developed at the Indian Agricultural Research Institute, New Delhi in 1935, is of the drum type. It consists of a masonry digester (fermentation tank), with an inlet pipe on one side for feeding cattle dung mixed with water into the plant and an outlet pipe on the other side for discharging the spent slurry (Fig. 13.29). The gas collects in a gas holder or drum made of mild steel. The gas holder is inverted over the slurry and moves up and down with the accumulation and discharge of gas.

Drumless Gas Plant

In this type, the gas holder and digester are combined in one unit (Fig. 13.30). There are no moving parts. The whole plant is an underground masonry well with a dome built over it. It is provided with a sloping inlet on one side and a rectangular outlet on the other for the escape of the slurry. In both designs, biogas formed through fermentation of the biomass is taken out through a central pipe fixed to the gas holder or drum.

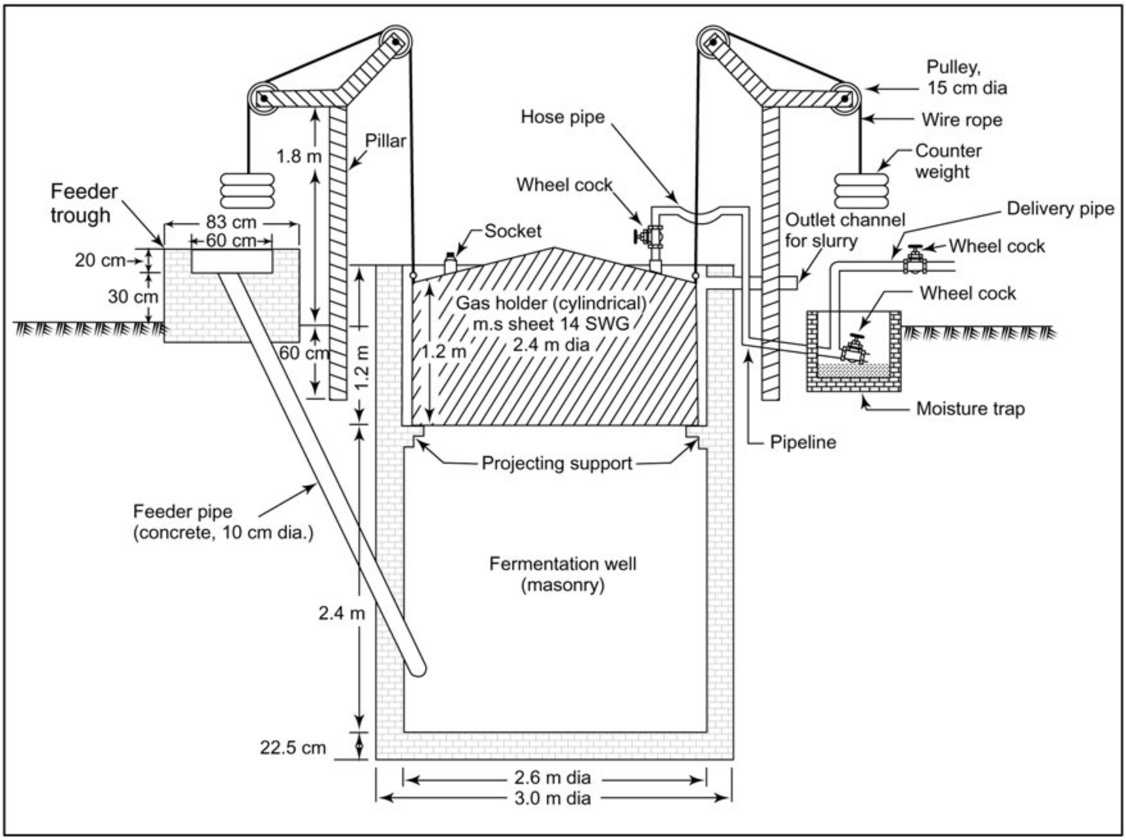


Fig. 13.29 Sectional view of a medium size drum type biogas plant, producing about 9 m^3 of fuel gas and requiring about 150 kg of cattle dung per day. The design specifications are suitable for a herd of 10–15 adult cattle

Adapted from: IARI Tech. Bul. Cow Dung Gas Plant (Anon., 1979)

Operation of Biogas Plants

To operate the biogas plant, a mixture of cattle dung or other animal excreta and water, in the ratio 1 : 1 is added as slurry to fill the digester. In a new plant, the production of gas may start in 5 to 10 days in summer, and 15 to 20 days in winter. When fresh dung is added into the digester, the digested slurry automatically overflows into a collection pit.

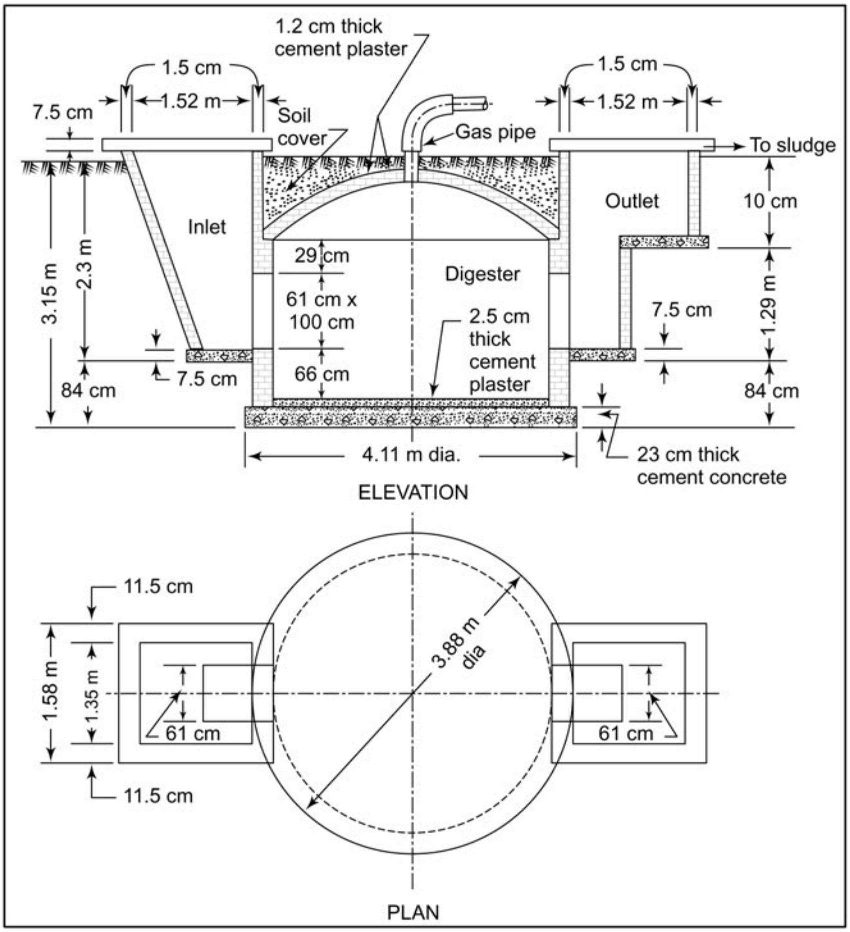


Fig. 13.30 Views of a drumless-type biogas plant

The maintenance requirements of gas plants include periodical draining of condensed moisture into the trap with a wheel cock, after detaching the gas pipe. In summer, if the slurry dries out to form a hard scum on the surface of the digester, water is added and the scum stirred with a pole. The gas holder is painted with an anti-corrosive paint once a year, preferably at the beginning of winter. Gas production, which slows down in the winter, is improved by adding cattle urine with the dung or by substituting about one-fifth of the dung with poultry droppings. It may also be improved by adding about 1 kg of powdered dry leaves or wheat straw mixed with urea (100 g) with every 50 kg of cattle dung.

Gas Production and Use

The volumetric composition of biogas produced from cattle dung is as follows:

Methane	50–60 per cent
Hydrogen	5–10 per cent
Carbon dioxide	30–40 per cent
Nitrogen	1–2 per cent
Hydrogen sulphide and oxygen	Traces

The rate of production of gas from the fermentation of cattle dung is about 90 l of biogas per kilogram of fresh dung, in the summer. Gas production in winter (temperature 5–10 ºC) is about 35 l of gas per kilogram of dung.

The gas can be used for cooking, lighting and running of internal combustion engines. The caolorific value of the gas is about 5 kcal/l. In comparison with diesel fuel, 1 m^3 (1000 l) of biogas is equivalent to 0.6 l of diesel oil for running engines.

13.5.3 Biogas Engine Pumping Set

Ordinary carburetting-type engines (petrol gasoline) can be adapted to run on biogas. In case of compression-ignition engines (diesel) adapted to run on biogas, a small part of the fuel continues to be diesel. A popular commercial make of biogas-run internal combustion engine working on the diesel cycle is designed to operate on about 80 per cent biogas and 20 per cent diesel oil. Minor modifications are made in the combustion chamber of the conventional diesel engine to adapt it for use with biogas. The engine is started on diesel oil and, after warming, is made to run on the biogas-diesel mixture for continued operation. The gas consumption of biogas engines is about 450 l (0.45 m^3) per brake horse power per hour of running.

Pumping Unit

Any of the common types of pumps—centrifugal or propeller—can be used with biogas engines. The pump can be coupled directly to the engine (Fig. 13.31) or operated by a belt drive. Low-head, high-discharge pumps are usually preferred for use with biogas engines.

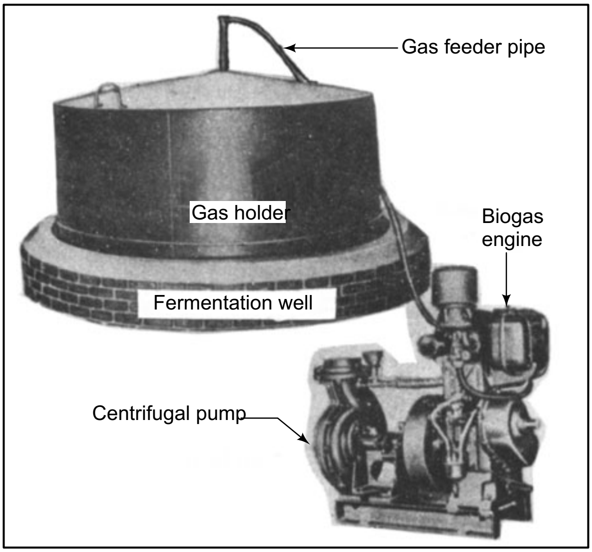


Fig. 13.31 Set-up of a biogas engine pumping set. A popular make of biogas engine illustrated above uses 80 per cent biogas and 20 per cent diesel fuel and generates 5 bhp at 1500 r.p.m. It requires about 0.45 m^3 (450 litres) of gas per bhp per hour of running.
Courtesy: Kirloskar Oil Engines Ltd.

13.6 UNIQUE REQUIREMENTS IN ADOPTING NON-CONVENTIONAL ENERGY SOURCES IN WATER PUMPING

Successful adoption of alternate energy sources in water pumping often requires marked departures from conventional practices of technical support to the rural community, water conveyance, cropping system and water-application methods, and provision of appropriate state subsidies wherever applicable.

Technical Support

Equipment utilizing renewable energy sources are basically non-conventional and require specific and well-organised technical support for their selection, installation, maintenance and repair. Technical skill in the management of these devices are almost completely lacking in rural areas. A programme of introduction of any of these devices should essentially have a group approach rather than resorting to sponsoring isolated units which are usually not supported by service facilities. If a large number of units of a particular kind, say windmills or solar pumps, are to be installed in a particular area, it is feasible to locate qualified technical personnel in a planned organisational system. These would include engineers, scientists and technicians with expertise in the management of the technical programme, including techno-economic feasibility surveys, design of the pumping system and ancillary facilities, installation under widely varying site conditions, and operation and maintenance of the equipment. Availability of spares at easily accessible locations is another requirement. It is often desirable that, during the initial phase of introducing non-conventional devices in the rural areas, the charges on installation and maintenance form an integral part of the supply of equipment. Programmes of continued situation-specific research and training of local technicians in the maintenance and repair of the non-conventional devices are essential so that the centralised support in this area can be gradually tapered off.

Cropping System

Alternate energy sources are often season variant. Hence, it will be necessary to adopt a cropping pattern to suit the availability of the energy source. In case of hydro-power operated equipment, stream flow is the highest during the monsoons. The major constraint is in the summer. In the Himalayan region, however, it is often possible to obtain adequate stream flow throughout the year, due to surface and subsurface flow contributions from snow melt. In case of solar pumps, the energy source is available throughout the year, except on rainy days. Under such a situation, it is necessary to adopt a diversified cropping system with different crops having their growing seasons and irrigation requirements spread over a long period to take full advantage of the available energy source. For instance, in northern India, a crop combination comprising pulses (gram), oilseeds (mustard) and grain crops (wheat) has been found to be suitable for operating a well-spread period of irrigation requirement. Such a combination would nearly double the command area of a solar pump, as compared to a monocrop situation when the entire land is allotted to a crop of wheat. It may be mentioned that even in the case of a single crop like wheat, there are early and late sown varieties which would result in a comparatively larger area irrigated, as compared to single variety of the same crop.

Variability in availability of the energy source is the least in case of biomass. However, the availability of green plant material is high during rainy seasons as compared to dry seasons.

Water Conveyance and Application in Low-Discharge Water Lifting Devices

Water lifts powered by alternate energy sources are essentially low-discharge units. They often require a lined channel or pipeline for conveyance as, otherwise, seepage losses would be excessive. Water could be diverted to the fields by using one or more siphon tubes made of plastic, rubber or metal.

Amongst the different surface irrigation methods, furrows or corrugations are the most suitable for management with low discharges.

13.7 BENEFIT-COST RATIO OF PUMPING PLANTS OPERATED BY ALTERNATE ENERGY SOURCES

Devices for utilising alternate energy sources are usually capital intensive, when their economics are worked out adopting the usual procedures. To be realistic, however, the socio-economic benefits derived from their adoption should also be taken into consideration. As discussed in the preceding pages, these devices have their application mainly in areas which are not easily accessible to conventional sources of energy, like electricity and petroleum fuels. These areas are usually inhabited by comparatively less-privileged sections of society. Further, all of them are renewable and pollution-free energy sources and available in plenty. Their utilization in small-scale irrigation would result in the saving of fossil fuel and electrical energy for heavier loads. While comparing the economics of any one of the alternative energy systems with the conventional diesel-engine powered ones, the subsidy given by the Government on diesel fuel for agricultural use would also have to be considered. Similarly, while comparing with electric motors, the cost of transmitting electricity to remote areas, which is almost exclusively borne by the State, and the energy loss in transmission would have to be considered. These factors point out the scope for extending governmental subsidy to pumping sets operated by alternative sources of energy, much in the same way as diesel fuel for agricultural use and rural electric supplies are subsidised.

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PROBLEMS

13.1 Estimate the horse power developed by a windmill having a rotor of 6 m diameter, when the wind speed is 15 km/hr. The density of air may be assumed to be 1.293 kg/m^3.

Ans. 1.053 hp

13.2 A windmill is to be designed to develop 0.75 hp at a wind speed of 15 km/h. Determine the diameter of the rotor.

Ans. 5.06 m

13.3 Determine the power output of a windmill, having a rotor diameter of 4 m, at a wind velocity of 15 km/h on the windward side and 10 km/h on the leeward side. Density of air is 1.293 kg/m^3.

Ans. 0.645 hp

13.4 A hydraulic ram operates at a drive head of 5 m and a delivery head of 25 m. The flow through the drive pipe is 12 l/s and the discharge at the outlet of the delivery pipe is 1.5 l/s. Compute the efficiency, adopting (i) D'Aubuisson's ratio and (ii) Rankine's formula.

Ans. (i) 55.55% (ii) 50.00%

13.5 Determine the weight of waste valve of diameter 10.5 cm, for a hydraulic ram. The valve is to start closing when the velocity of flow through it is 2.0 m/s.

Ans. 1.502 kg

13.6 Assuming the following conditions, estimate the minimum expected flow rate of a source of water for installing a hydraulic ram in a rural water supply scheme:

Vertical fall	10 m
Vertical lift	70 m
Population of village	350
Rate of increase of population	25% in 15 years
Water allowance	50 l/day/person
Efficiency of ram	60%

Ans. 2.17 l/s

SHORT QUESTIONS

I. State True (T) or False (F).

1. Fossil fuels are non-renewable energy sources.
2. Wind, sun, and biomass are conventional energy sources.

3. Water lifting devices using alternative energy sources are suitable mainly in small scale irrigation.
4. If the wind speed doubles then the power in the wind increases by a factor of eight.
5. In India, the period of the high wind velocity is mainly the winter months.
6. In India, the high wind velocities prevail in coastal areas and the arid and semi-arid zone.
7. Wind power is proportional to the square of the area swept by the windmill rotor.
8. At very high speed of the rotor, no power is developed by the windmill.
9. The stress on the windmill tower varies as the square of the wind velocity.
10. The wind speed increases with increasing height.
11. Vertical-axis windmills are most commonly used in water lifting.
12. Windmills run at variable speeds.
13. Centrifugal pumps are most suitable for use with windmills.
14. The wind velocity at the rotor is the average of wind velocities at the front and rear sides of the rotor.
15. Hydraulic ram is suitable in hilly areas.
16. Hydraulic ram utilizes the kinetic energy of falling water from moderate height to raise a part of it a greater height.
17. Hydraulic ram works on the principle of water hammer.
18. Hydraulic ram is an impulse pump.
19. In order to develop maximum impulse in hydraulic ram, the supply pipe should be as short as possible.
20. The hydraulic ram works all 24 hours in a day.
21. The lift magnification factor is the ratio between supply head and delivery head.
22. The efficiency of a hydraulic ram varies directly as the magnification factor.
23. In hydraulic ram, the rate of flow of water through drive pipe should be at least three times the rate of discharge through the delivery pipe.
24. The discharge of the hydram is directly proportional to the velocity head.
25. The waste valve is a component of hydraulic ram.
26. Hydro-power could be utilized in pumping water.
27. Most part of India experience 250-300 sunny days in a year.
28. Standard solar day means that a collector surface receives 8 kW-h of energy per day per square metre of its surface.
29. Photovoltaic cells convert the sunlight into electricity.
30. Both the thermal and sunlight part of solar energy can be used for pumping water.
31. Teflon is the most commonly used material for making solar cells.
32. Solar arrays consist of connecting solar cells into the series-parallel configuration.
33. Thermal power systems are preferred over photovoltaic power systems in operating pumps.
34. The photovoltaic power is utilized to operate DC electric motors.
35. The submersible pump system is more efficient and suitable for the photovoltaic system.
36. The power developed by solar array ranges from 200 to 240 watts per square metre of the panel.
37. The output of the solar array is independent of intensity of the incoming radiation.
38. Organic residues are the renewable source of energy.
39. Biogas is a mixture of gases produced by the aerobic fermentation of easily decomposable cellulosic materials.
40. Ordinary carbureting-type engines can be adapted to run on biogas.

Ans. True: 1 3 4 6 8 9 10 12 14 15 16 17 18 20 23 25 26 27 29 30 32 34 35 38 40

II. Select the correct answers.

1. The example of renewable energy source is
   (a) coal (b) nuclear fuel
   (c) petroleum (d) wind
2. The minimum wind speed required for operation of a windmill usually ranges from
   (a) 2-km/hr (b) 4–6 km/hr
   (c) 6–8 km/hr (d) 8–10 km/hr
3. At a particular wind velocity the energy from the wind varies as:
   (a) square root of the wind velocity and the duration of wind
   (b) square of the wind velocity and the duration of wind
   (c) cube of the wind velocity and the duration of wind
   (d) cube root of the wind velocity and the duration of wind
4. The stress on the windmill tower varies as:
   (a) wind velocity (b) square of wind velocity
   (c) square root of wind velocity (d) cube of wind velocity
5. Aerodynamically most efficient windmills are:
   (a) propeller type (b) cylinder type
   (c) anemometer type (d) sail type
6. An example of high head water turbine is:
   (a) Propeller (b) Kaplan
   (c) Pelton (d) Banki
7. The minimum fall in altitude required for working of hydraulic ram is:
   (a) 1 m (b) 3 m
   (c) 6 m (d) 10 m
8. In hydraulic ram the waste valve is also called:
   (a) delivery valve (b) impulse valve
   (c) check valve (d) air feeder valve
9. Most hydraulic rams works at the best efficiency if the lift magnification ratio is limited to:
   (a) 4:1 (b) 8:1
   (c) 12:1 (d) 24:1
10. In hydraulic ram the lift magnification factor is the ratio between:
    (a) delivery head and supply head (b) supply head and delivery head
    (c) input energy and output energy (d) delivery head and total head
11. The size of the drive pipe in hydraulic ram is so selected that ratio of rate of flow of water through it to that of discharge pipe as at least:
    (a) two (b) three
    (c) four (d) five
12. In solar thermal pump, the commonly used pump is:
    (a) centrifugal pump (b) submersible pump
    (c) jet pump (d) piston pump
13. The most commonly used material for making solar cells is:
    (a) cadmium (b) gallium
    (c) silicon (d) silver

14. How much is the decrease in efficiency of silicon solar cell for each 1ºC rise in temperature above the standard day time temperature of 28ºC?
    (a) 1/2 per cent (b) 2 per cent
    (c) 5 per cent (d) 8 per cent
15. The rate of production of biogas from the fermentation of cattle dung in summer is about:
    (a) 40 l per kg of fresh dung (b) 90 l per kg of fresh dung
    (c) 130 l per kg of fresh dung (d) 150 l per kg of fresh dung

Ans. 1. (a) 2. (c) 3. (c) 4. (b) 5. (a) 6. (c) 7. (a) 8. (b)
9. (a) 10. (a) 11. (b) 12. (d) 13. (c) 14. (a) 15. (b)

14

Techno-Economic Evaluation of Projects on Wells and Pumps

Water well and pump projects require large investments. The rapid increase in ground water development has focussed the attention of financing institutions and users on the need to establish the technical and economic feasibility of a project proposal. The National Bank for Agriculture and Rural Development, the Agricultural Finance Corporation, nationalised banks and other commercial and cooperative banks insist on appropriate techno-economic feasibility reports to establish the credit worthiness of projects on wells and pumps.

The technical appraisal of a project on wells would require the application of suitable techniques for assessing ground water resources in the scheme area, and considerations on the design of wells to match the characteristics of the ground water formations. Equal attention is given to the selection of pumps to match the characteristics of the well and to suit the source of power available.

The economic analysis must take full account of all attributable costs and benefits. Appropriate arrangements will be required if the project is to recover the cost from the beneficiaries. The financial feasibility of the investment is studied through various discounting techniques, like present worth method, benefit-cost ratio and internal rate of return, to ensure that the investment is worthwhile. The analysis is done on the basis of data collected from the project area.

TECHNICAL EVALUATION

The technical appraisal of a project on wells and pumps is carried out to ensure

1. The availability of ground water resources for development,
2. The optimum design of wells, and
3. Proper selection, installation, operation and maintenance of pumps.

14.1 AVAILABILITY OF GROUND WATER RESOURCES

The ground water available for development is the annual replenishment less the annual draft. The ground water replenishment of an area can be computed by estimating the recharge from the different components contributing to the ground water using appropriate norms, or from an analysis of the water balance, based on data on the fluctuations in the water table.

The various components of ground water recharge include the recharge from rainfall, canal seepage, if any, seepage from irrigation reservoirs/tanks, deep percolation from irrigated fields, and inflow from neighbouring areas. In the absence of data on these items from the project area, data from similar areas or the broad guidelines developed by the Central Ground Water Board (CGWB) and the recommendations of other agencies/organizations working on water resources development can be suitably adopted.

14.1.1 Estimation of Ground Water Recharge

In India, till the year 1972, ground water resources evaluation was being done on a sectoral or regional basis for the projects availing institutional finance. The estimates were based on the data obtained by the Geological Survey of India or the Exploratory Tube Well Organisation (now Central Ground Water Board) and the state ground water organizations. In 1972, guidelines for an approximate evaluation of the ground water potential of a project area was circulated by the Ministry of Agriculture, Government of India, to all State Governments and related banking institutions. These norms, which were very broad, were used in ground water estimation till 1983, in evaluating projects where actual field data were not available. In 1984, the Ground Water Estimation Committee, appointed by the Ministry of Irrigation, gave more elaborate guidelines to estimate the recharge to ground water from different sources. These guidelines were further revised in 1997 by Ground Water Resource Estimation Committee, Ministry of Water Resources, Government of India (GWREC, 1997). These are based on two approaches, namely rainfall infiltration factor method and ground water level fluctuation method.

Rainfall Infiltration Factor Method

The method is used in areas where ground water level monitoring is not adequate in space and time. The norms for recharge from rainfall and other sources are described below.

1. Recharge from Rainfall

The recharge from rainfall, under different soil conditions, is given in Table 14.1

The same recharge factor may be used for both monsoon and non-monsoon rainfall. If the normal rainfall during non-monsoon period is less than 10 per cent of normal annual rainfall the recharge may be taken as zero during this period.

Usually, the recommended values should be used for assessment, unless sufficient information is available to justify the use of minimum, maximum or other intermediate values. An additional 2% of rainfall factor may be used in such areas or part of the areas where watershed development with associated soil conservation measures are implemented. The additional factor is subjective and is separate from the contribution due to the water conservation structures such as check dams, *nala* bunds, percolation tanks etc. The norms for the estimation of recharge due to these structures are provided separately. The values of normal rainfall are obtained from the Meteorological Department.

TABLE 14.1 Recharge from Rainfall

Percentage (%)

Soil conditions	Recommended value	Minimum value	Maximum value
(a) *Alluvial areas*			
Indo-Gangetic and inland areas	22	22	25
East coast	16	14	18
West coast	10	8	12
(b) *Hard rock areas*			
Weathered granite, gneiss and schist with low clay content	11	10	12
Weathered granite, gneiss and schist with significant clay content	8	5	9
Granulite facies like charnockite etc.	5	4	6
Vesicular and jointed basalt	13	12	14
Weathered basalt	7	6	8
Laterite	7	6	8
Semiconsolidated sandstone	12	10	14
Consolidated sandstone, quartzite, limestone (except cavernous limestone)	6	5	7
Phyllites, shales	4	3	5
Massive poorly fractured rock	1	1	3

2. Recharge due to Seepage from Canals

The following guidelines, given by CGWB (GWREC, 1997) may be adopted in most of the area, except where project studies undertaken earlier have indicated different norms.

1. For unlined canals in normal types of soil, with some clay content along with sand, 15 to 20 ha-m/day/10^6 m^2 of wetted area of the canal or 1.8 to 2.5 cumecs/10^6 m^2 of wetted area
2. For unlined canals in sandy soils, 25 to 30 ha-m/day/10^6 m^2 of wetted area or 3.0 to 3.5 cumecs/ 10^6 m^2 of wetted area.
3. For lined canals and canals in hard rock areas, 20 per cent of above values for unlined canals may be used.

   The above values are valid if the water table is relatively deep. In shallow water table and waterlogged areas, the recharge from canal seepage may be suitably reduced.

3. Return flow from Irrigated Fields

The recharge due to return flow from irrigation may be estimated, based on the source of irrigation (ground water or surface water), the type of crop (paddy, non-paddy) and the depth of water table below ground level, using the norms given in Table 14.2.

TABLE 14.2 Norms for Computation of Return Seepage as Percentage of Application for Irrigated Fields.

Source of irrigation	Type of crop	Water table below ground level		
		< 10 m	10-25 m	> 25 m
Ground water	Non-paddy	25	15	5
Surface water	Non-paddy	30	20	10
Ground water	Paddy	45	35	20
Surface water	Paddy	50	40	25

Notes:

(i) For surface water, the recharge is to be estimated based on water released at the outlet. For ground water, the recharge is to be estimated based on gross draft.

(ii) Where continuous supply is used instead of rotational supply, an additional recharge of 5 per cent of application may be used.

(iii) Where specific results are available from case studies, the adhoc norms are to be replaced by norms evolved from these results.

4. Recharge from Storage Tanks and Ponds

The recharge from storage tanks and ponds may be assumed as 1.4 mm/day for the period in which the tank has water, based on the average area of water spread. If data on the average area of water spread is not available, 60 per cent of the maximum water spread area may be used instead of average area of the water spread.

5. Recharge from Percolation Tanks

The recharge from percolation tanks may be considered as 50 per cent of gross storage, considering the number of fillings, with half of this recharge occurring in the monsoon season, and the balance in the non-monsoon season.

6. Recharge Due to Check Dams and Nala Bunds

The recharge due to check dams and *nala* bunds is assumed as 50 per cent of gross storage (assuming annual desilting maintenance exists) with half of this recharge occurring in the monsoon season, and the balance in the non-monsoon season.

7. Contribution from Influent Seepage

Influent seepage from rivers with definite influent characteristics may be computed using the Darcy's law

$$Q = T\,I\,L \tag{14.1}$$

Where, Q = rate of flow, m^3/day

T = transmissibility of aquifer for the thickness above river bed, m^2/day

I = hydraulic gradient, m/km

L = length of section through which flow is taking place, km

Ground Water Level Fluctuation Method

To obtain a fairly accurate estimate of ground water recharge during the monsoon period, the water balance approach, based on water table fluctuations and specific yield, should be applied as far as possible. The monitoring of water level network stations should be adequate in space and time to get a realistic behaviour of the effects of ground water development on the ground water regime.

Since the measurement of the highest post-monsoon water level is often difficult in view of the non-approachability of a large number of observation wells during and immediately after the monsoon, the ground water recharge may be estimated based on April-June and October-November water level fluctuations, for areas receiving rainfall from the south-west monsoon. Local variations may, however, be taken into consideration while computing the recharge. Ground water contours should preferably be drawn for each basin or sub-basin, and the administrative unit super-imposed to estimate the ground water resources for each block.

The specific yield data may be computed from pumping tests in the project area. Alternatively, the results of studies by different agencies under similar hydrogeological situations may be adopted. As a guide, the specific yield values for different types of geological formation given in Table 14.3 may be used.

TABLE 14.3 Norms for Specific Yield

Percentage (%)

Geological formation	Recommended value	Minimum value	Maximum value
(a) *Alluvial areas*			
Sandy alluvium	16.0	12.0	20.0
Silty alluvium	10.0	8.0	12.0
Clayey alluvium	6.0	4.0	8.0
(b) *Hard rock areas*			
Weathered granite, gneiss and schist with low clay content	3.0	2.0	4.0
Weathered granite gneiss and schist with significant clay content	1.5	1.0	2.0
Weathered or vesicular, jointed basalt	2.0	1.0	3.0
Laterite	2.5	2.0	3.0
Sandstone	3.0	1.0	5.0
Quartzite	1.5	1.0	2.0
Limestone	2.0	1.0	3.0
Karstified limestone	8.0	5.0	15.0
Phyllites, Shales	1.5	1.0	2.0
Massive poorly fractured rock	0.3	0.2	0.5

Note: Usually the recommended values should be used for assessment, unless sufficient data based on field study are available to justify the minimum, maximum or other intermediate values.

The water table fluctuations in an aquifer correspond to the rainfall during the year of observation and recharge due to seepage from canals and return flow from irrigation water, recharge from storage tanks/ponds and from water conservation structures is given by

$$R_{rf} = h.\ S_y.\ A + D_G - R_C - R_{SW} - R_t - R_{gw} - R_{wc} \qquad (14.2)$$

Where,

R_{rf} = recharge from rainfall
R_C = recharge due to seepage from canals
R_{sw} = recharge from surface water irrigation
R_t = recharge from storage tanks and ponds
R_{gw} = recharge from ground water irrigation
R_{wc} = recharge from water conservation structures
D_G = gross draft in the command area
h = rise in ground water level
A = area of the unit for recharge assessment
S_y = specific yield

Eq. 14.2 gives rainfall recharge in a particular monsoon season for the associated monsoon season rainfall. This estimate should be normalized for the normal monsoon season rainfall, which in turn is obtained as the average of the monsoon season rainfall for the recent 30 to 50 years. The following steps are involved.

(a) Computation of a set of pairs of data on rainfall recharge R_i and associated rainfall r_i = 1 to N in which N is atleast 5.
(b) Considering only those values of R_i and r_i in which R_i is greater than zero for further computation in the normalisation procedure.
(c) Each pair of R_i and r_i are used to obtain $[(R_{rf}\text{(normal)}]_i$ as

$$[R_{rf}\text{(normal)}]_i = R_i \times \frac{r\text{(normal)}}{r_i}$$

The monsoon season rainfall recharge R_{Jf} (normal) is then computed as,

$$R_{jf}\text{(normal)} = \frac{\sum_{i=1}^{N} 1[R_{rf}\text{ (normal)}]_i}{N}$$

The rainfall recharge as computed above is to be compared with rainfall recharge estimated by rainfall infiltration factor method. The per cent difference (PD) is computed as

$$PD = \frac{[R_{rf}\text{ (normal, }W_{tfm}) - R_{rf}\text{ (normal, }r_{ifm})]}{R_{rf}\text{ (normal, }r_{ifm})} \times 100$$

Where,

R_{rf}(normal, W_{tfm}) = rainfall recharge for normal monsoon season rainfall estimated by the water table fluctuation method

R_{rf} (normal, r_{ifm}) = rainfall recharge for normal monsoon season rainfall estimated by rainfall infiltration factor method

The rainfall recharge for normal monsoon rainfall is finally adopted as per criteria given below:

(i) If PD is greater than or equal to –20 per cent and less than or equal to +20 per cent, R_{rf} (normal) is taken as the value estimated by the water table fluctuation method.
(ii) If PD is less than –20 per cent, R_{rf} (normal) is taken as equal to 0.80 times the value estimated by the rainfall infiltration factor method.
(iii) If PD is greater than +20 per cent, R_{rf} (normal) is taken as equal to 1.2 times the value estimated by the rainfall infiltration factor method.

The total recharge during the monsoon season for normal monsoon season rainfall condition includes recharge from rainfall and other sources and is finally obtained as.

R (normal) = R_{rf} (normal) + R_c + R_{sw} + R_f + R_{gw} + R_{wc} for command areas

Where,

R (normal) = total recharge during monsoon season
R_{rf} (normal) = rainfall recharge during monsoon season for normal monsoon season rainfall
R_c = recharge due to seepage from canals in the monsoon season for the year of assessment
R_{sw} = recharge from surface water irrigation in the monsoon season for the year of assessment
R_t = recharge from tanks and ponds in the monsoon season for the year of assessment
R_{gw} = recharge from ground water irrigation in the monsoon season for the year of assessment
R_{wc} = recharge from water conservation structures in the monsoon season for the year of assessment

The recharge from sources other than rainfall is estimated as per the norms presented in Sec.14.1.1.

Ground Water Recharge During Non-Monsoon Periods

The ground water recharge during non-monsoon periods includes recharge from rainfall, seepage from canals, return flow from canal irrigation, return flow from ground water irrigation, recharge from water conservation structures and from tanks/ponds. The recharge from rainfall may be estimated using rainfall infiltration factors (Table 14.1) provided the normal rainfall is greater than 10 per cent of the normal annual rainfall, otherwise the recharge due to rainfall in non-monsoon season may be taken as zero. The other components of recharge may be estimated using standard norms as already discussed.

In the areas receiving high rainfall during the south-west and north-east monsoons, but separated by a dry intervening period, the well hydrograph would show two distinct trends. In such cases, the contribution from winter rainfall can be evaluated by a similar method as the monsoon rainfall. For this, adequate water level data during the winter is required. The ground water recharge can be computed by adopting the water level fluctuation and specific yield approaches. The total ground water recharge would be the sum of monsoon and non-monsoon recharges.

14.1.2 Ground Water Assessment in Saline Areas

The areas with brackish/saline ground water be delineated and the ground water resource of these areas be computed separately. In case adequate data on ground water level is not available, the recharge assessment may be based on rainfall infiltration factor method, using the norms prescribed in Sec. 14.1.1.

14.1.3 Estimation of Static Ground Water Resource

The equation of water available for development is usually restricted to long term average recharge or, in other words, to dynamic resource. However, recent data indicate that even in States with a high degree of ground water development, water levels have not shown decline trend. It is, therefore, considered that the temporary depletion of water table taking place during drought years is made up during years of high rainfall. In other words, the utilisation of static reserves and the consequent depletion in water levels in drought years is made up during years of high rainfall. This may be studied by comparing the long-range rainfall graph and the water table hydrograph, to establish the periodical recharge. In such areas, it would be desirable that a ground water reservoir is pumped to the optimum limit to provide adequate scope for its recharge during the following monsoon period. Ground water available below the zone of natural water level fluctuations can also be partly utilised by some effective means of extraction. Therefore, an estimate of such a static ground water reserve is essential for optimum utilisation and planning for future development of the ground water resources of an area.

The static ground water resource in an area may be computed as follows:

Static ground water reserve (m^3) = Thickness of the aquifer below the zone of water level fluctuations (m) down to exploitable limit × Areal extent of the aquifer (m^2) × Specific yield of the aquifer (fraction)

The development of the static resource has to be done carefully and cautiously.

14.1.4 Availability of Ground Water for Irrigation

The annual availability of ground water for irrigation = Annual availability of ground water—requirement of ground water for domestic and industrial use. In the absence of data, the requirement of ground water for domestic and industrial use may be assumed as 60 litres per day per head. To determine the potential for future irrigation development from ground water, the existing ground water draft for irrigation has to be deducted from the net ground water availability for irrigation.

14.1.5 Categorisation of Areas for Ground Water Development

The areas for ground water development can be categorized according to stage of ground water development and long-term ground water trend.

(i) *Stage of ground water development:* The stage of ground water development is defined as percentage of ground water development

$$= \frac{\text{Existing ground water draft for all uses}}{\text{Annual ground water availability}} \times 100$$

The stage of ground water should be obtained separately for command and non-command areas.

(ii) *Long term ground water trend:* While computing the stage of ground water development, the ground water draft is based on number of assumptions such as number of tubewells, draft of each tubewell etc., therefore an alternate index of the present status of ground water regime, based on long term trend of ground water level is desirable. The average water level obtained from the different observation wells in the assessment unit giving the variation of pre and post-monsoon water level trend for a minimum period of 10 years may be plotted on the same figure. Separate figures may be obtained for command and non-command areas in the unit if both types of areas are present.

If the ground water resource assessment and the trend of long term water levels contradict each other, this anomalous situation requires a review of ground water resource computation, as well as the reliability of water level data. The categorization of areas based on long term ground water trend are given in Table 14.4.

TABLE 14.4 Categorization of Areas Based on Long Term Ground Water Trend

Category	Condition
(i) Safe area with potential for development	(a) Stage of ground water development is less than 70 per cent and there is no significant long term decline of pre- or post-monsoon ground water levels (b) Stage of ground water development is more than 70 per cent but less than 90 per cent and both pre- and post-monsoon ground water level do not show a significant long term decline.
(ii) Semi critical areas for cautious ground water development	Stage of ground water development is more than 70 per cent but less than 90 per- cent and either pre-monsoon or post-monsoon ground water levels shows a significant long term decline.
(iii) Critical areas	(a) Stage of ground water development is less than 100 per cent and either pre- or post-monsoon ground water levels shows a significant long term decline. (b) Stage of ground water development is more than 90 per cent but less than 100 per cent but both pre- and post-monsoon ground water levels shows a significant long term decline. (c) Stage of ground water development is more than 100 per cent, but either pre- or post-monsoon ground water level does not show a significant long term decline.
(iv) Over-exploited areas	Stage of ground water development is more than 100 per cent and both pre- and post-monsoon ground water levels show a significant long term decline.

14.1.6 Estimation of Ground Water Draft

The number of specific type of ground water structure multiplied by its average annual unit draft gives the ground water draft. The number of structures are determined on the basis of well census conducted by the state and updating the same based on growth rate. The unit draft should be based on the well yield capacity, its command area and techno-economic viability of a ground water structure.

Ground water draft can also be estimated by alternate methods based on: (a) electric power consumption for agricultural pump sets, and (b) statistics of area irrigated by ground water. The annual average gross unit draft for various type of ground water structures in different states of India are given in Table 14.5.

TABLE 14.5 Average Annual Gross Draft for Ground Water Structures in Different States

S. no.	State	Type of ground water structure	Average gross unit draft (ha-m)
1.	Andhra Pradesh	Dug well with *mhot*	0.35
		Dug well with pumpset	0.65
		Bore well with pumpset	1.30
		Shallow tube well	2.05
		Medium tube well	4.10
		Deep tube well	5.85
2.	Assam	Shallow tube well with pumpset	3.00
3.	Bihar	Dug well	0.60
		Private tube well with pumpset	1.00
		Bamboo boring with pumpset	0.75
		Deep tube well	30.00
4.	Gujarat	Dug well with pumpset	0.80
		Bore well with pumpset	1.20
		Private shallow tube well	1.85
		Medium deep tube well	6.00
		Deep tube well	30.00
5.	Haryana	Dug well with pumpset	1.50
		Private shallow tube well with pumpset	1.81
		Deep tube well	15.00
6.	Himachal Pradesh	Medium deep tube well and pumpset	2.50
7.	Karnataka	Dug well with pumpset	0.90
		Bore well with pumpset	1.70
		Dug cum bore well with pumpset	1.98
8.	Kerala	Dug well with pumpset	0.50
		Bore well with pumpset	0.70
9.	Madhya Pradesh	Dug well with *mhot*	0.80
		Dug well with pumpset	1.50
		Bore well with pumpset	1.50
		Private shallow tube well with pumpset	3.00
10.	Maharashtra	Dug well with *mhot*	0.45
		Dug well with pumpset	1.57

(*Contd.*)

TABLE 14.5 (*Contd.*)

S. no.	State	Type of ground water structure	Average gross unit draft (ha-m)
11.	Orissa	Dug well with *mhot*	0.21
		Dug well with pumpset	1.00
		Filter point with pumpset	2.10
		Private tube well with pumpset	7.00
		Deep tube well with pumpset	17.50
12.	Punjab	Shallow tube well with pumpset	1.3-3.40
		Deep tube well with pumpset	18.00
13.	Rajasthan	Dug well with pumpset	0.52
		Private tube well with pumpset	1.40
		Dug-cum-bore well with pumpset	1.23
		Deep tube well	2.28
14.	Tamil Nadu	Dug well with pumpset	0.4-1.00
		Private tube well with pumpset	1.0-2.00
		Bore well with pumpset	1.00
15.	Tripura	Shallow tube well with pumpset	3.00
		Artesian well	0.37
16.	Uttar Pradesh	Dug well with *mhot*	0.37
		Dug well with pumpset	0.75
		Private tube well with pumpset	3.70
		Deep tube well	22.00
17.	West Bengal	Dug well with pumpset	0.30
		Private tube well with pumpset	1.52
		Deep tube well with pumpset	18.50

14.2 DESIGN OF WELLS AND SELECTION OF EQUIPMENT FOR PUMPING

The well is designed according to the guidelines given in Chs 3 and 4, for open wells and tube wells, respectively. The pumps are selected as per the procedure described in Sec. 9.8. The selection of particular type of Pump and accessories is made as per the procedure described in Chapter 9 to 12.

14.3 ECONOMIC EVALUATION

An investment on a project on wells and pumps is economically justifiable only if it shows a profit. It is, therefore, important that the project is analysed from the economic angle and its profitability assessed. The returns from the project should have a clearly higher value than the cost of all the inputs. Economic evaluation includes the determination of total benefits and total costs.

The economic analysis is performed in a series of steps. The resulting physical consequences of the project are predicted. A monetary value is placed on each physical consequence. A discount rate is selected and applied to convert the predicted time stream of monetary values into an equivalent single number. For example, in case of a ground water development project, the cost of installation of wells and pumps, their annual cost of each short-lived item, and the benefit resulting from the increased yield of every crop in each year, should be determined. The various methods used to carry out the economic analysis of water well and pump projects include.

1. the benefit-cost method,
2. the present worth method, and
3. the internal rate of return method.

14.3.1 Benefit-Cost Method

The economic feasibility of a project is based on the benefit-cost relationship. The total benefit B should be more than the total cost C. A project is economically feasible under the following conditions:

$$B > C$$

$$B\text{-}C > 0$$

Or $$B/C > 1$$

It is essential to take into consideration the time element of both benefits and costs. The costs include the fixed cost, which are incurred usually in the initial stages. These include the cost of planning and design, equipment and accessories, installation and commissioning. The second are the annual costs usually termed OMR (operation, maintenance and replacement) and the expenditure on taxes and insurance. Annual benefits are always considered. For a comparison of benefits and costs, both are expressed in the same terms, namely, present worth values or annual values, which include amortization on the initial investment.

In situations where several competing projects are to be considered within a limited budget, or alternative proposal are available, they are to be compared and ranked in a series of decreasing values, such as decreasing net benefits or decreasing returns on the money invested.

In comparing benefits to costs, two alternative criteria are available, namely, the expression of net benefit B-C, provides the relative returns from each unit of the money invested. When funds are limited, it is advisable to use the B/C criterion which will allocate the available funds to a combination of smaller, efficient projects rather than one or two large ones.

14.3.2 Present-Worth Method

In this method, the algebraic sum of benefits minus costs over the life of the project are converted into their present worth. The present worth is defined as follows:

$$PW = \sum_{t=i}^{n} \left(\frac{P}{F}, i\%, t \right) (B_t - C_t) \tag{14.3}$$

Where, t = period of analysis, varying from 1 to n years

C_t = cost in subscripted year, Rs

B_t = benefit in subscripted year, Rs

i = discount rate

(P/F, i%, t) is the abbreviation for the single payment present worth factor. The notation P and F imply future and present amounts, based on discount rate and period of analysis. For a given value of discount rate i and period n, the present-worth factor is

$$\left(\frac{P}{F}, i\%, t \right) = \frac{P}{F}$$

Which is defined as

$$\frac{P}{F} = \frac{1}{(1+i)^n} \tag{14.4}$$

In Eq. (14.4), the value of i is taken as a fraction.

When the annual net benefit

$$B' = B_t - C_t$$

remains constant over the project life, except the initial first cost K, Eq. (14.3) may be modified to

$$PW = -K + B'\left(\frac{P}{A}, i\%, n\right) \tag{14.5}$$

Where, K = initial first cost, Rs

B' = annual net benefit, Rs

(P/A, $i\%$, n) is the abbreviation for the series present-worth factor. A denotes equal amounts at the end of each of n years. For a given value of discount rate i and period n, the series present-worth factor is

$$\left(\frac{P}{A}, i\%, n\right) = \frac{P}{A}$$

Which is defined as

$$\frac{P}{A} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{14.6}$$

In Eqn. (14.6), the value of i, is taken in fraction.

EXAMPLE 14.1 The initial investment on a tube well and pump project is Rs. 50,000. The yearly net benefit is Rs. 8000. Estimate the present worth if the project period is 20 years and discount rate is 10%.

Solution

Since the annual net benefit over the project period is constant, the present worth, is given by

$$PW = -K + B'\,(P/A, i\%, n)$$

$$K = \text{Rs } 50{,}000$$

$$B' = \text{Rs } 8000$$

$$\left(\frac{P}{A}, i\%, n\right) = \frac{P}{A} = \frac{(1+i)^n - 1}{i(1+i)^n}$$

$$= \frac{(1+0.10)^{20} - 1}{0.10\,(1+0.10)^{20}} = \frac{6.73 - 1}{0.673} = 8.51$$

$\therefore$ PW = –50,000 + 8000 × 8.51 = Rs. 18,080.00

14.3.3 Internal Rate of Return

The profitability of a project may be measured by means of a comparison between its benefits and costs, through the use of the internal rate of return. The internal rate of return, r, is defined as the interest rate which will provide the equalization of total cost to benefits. Considering the annual values of benefits and costs, the internal rate of return may be expressed mathematically as

$$K \times C_{rf} = B' \tag{14.7}$$

Where, K = initial investment, Rs

B' = annual net benefit, Rs

$$C_{rf} = \text{capital recovery factor} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{14.8}$$

r = internal rate of return, fraction

Alternatively,

$$C_{rf} = \frac{B'}{K}$$

The internal rate of return, r, is the rate of interest which will satisfy the relationship

$$C_{rf}(r, n) = \frac{B'}{K}$$

Conversely

$$\frac{r(1+r)^n}{(1+r)^n - 1} = \frac{B'}{K} \tag{14.9}$$

If the value of r is higher than the market value of interest on investments, the project is economically feasible. When projects are ranked in order of merit, the internal rate of return r will give a different series than that obtained by the B/C ratio criterion. The method is suitable when the money for the initial investment is limited. Both criteria will, however result in similar ranking when comparing projects with similar B/C ratios.

Example 14.2 In a tube well and pump project, the initial cost is Rs 50,000. The project period is 20 years. The annual net benefit is Rs 7000. Estimate the internal rate of return.

Solution

The internal rate of return is given by Eq. (14.9)

$$\frac{r(1+r)^{20}}{(1+r)^{20} - 1} = \frac{B'}{K}$$

$$\therefore \quad \frac{r(1+r)^{20}}{(1+r)^{20} - 1} = \frac{B'}{K} = \frac{7000}{50000} = 0.14$$

The value of r is to be obtained by trial and error. Assuming different values of the rate of return, the capital recovery factor is calculated. The internal rate of return r, which gives the capital recovery factor close to the given value, is chosen. Capital recovery factor values for different values of r are given below:

r	0.10	0.11	0.12	0.13	0.14	0.15
C_{rf}	0.117	0.125	0.135	0.142	0.150	0.160

As calculated above, the internal rate of return is 13 per cent, as it gives the desired value of the capital recovery factor of 0.14. The exact value of the rate of return may also be worked out by plotting the assumed values of the rate of return versus the respective calculated values of the capital recovery factor. The internal rate of return is determined from the graph with respect to the given value of recovery factor.

14.3.4 Enumeration and Evaluation of Costs and Benefits

In the economic evaluation of projects on wells and pumps it is important to include all costs and benefits in the analysis. The annual cost of a project includes both fixed and variable costs. The fixed costs will include depreciation plus interest on investment.

Fixed costs, also referred to as investment or initial costs, include the following:

1. Planning and design costs
2. Cost of wells, pumps, electric motors/engines and pumping plant accessories, and installation
3. Pump house, if any
4. Electric power connection, monitoring, metering and recording equipment
5. Water conveyance and distribution systems, if included in the project
6. Equipment for water application, sprinkler/drip irrigation equipment, if used.

Annual operating costs include the following

1. Fuel/electricity
2. Lubricants, minor repairs and painting
3. Replacement of short-lived elements
4. Operating manpower (Manpower costs include salaries, social benefits, housing, insurance, medical treatment, transportation and other similar items).

Different methods are used for obtaining the annual amortized value of the fixed cost. A simple procedure is to calculate the interest on the average value of the installation at the prevailing interest rate:

$$\text{Annual interest cost} = \frac{(\text{Value of installation} - \text{Salvage value}) \times \text{Interest rate}}{2}$$

Depreciation: Depreciation is the loss in value of the pumping plant due to operation or age.

$$\text{Annual depreciation} = \frac{\text{Original cost} - \text{Salvage value}}{\text{Useful life in year}}$$

The average interest on the investment plus the depreciation cost gives the annual fixed cost.

A more precise method of computing the annual amortized fixed cost is to take into account the expected life of the item and the interest rate. In this method, the fixed cost is based on the present worth multiplied by the capital recovery factor. The capital recovery factor is calculated using Eq. (14.8), with r as rate of interest in fraction and n as anticipated service period of the project in years.

When the expected service period is specified in hours of operation, the same in years is calculated by dividing the total hours of operation by the average annual hours of operation.

The expected service period and annual maintenance and repair costs of various components of wells and pumps is given in Table 14.6. These figures are applicable under normal conditions with good quality ground water. In case of poor quality ground water and abnormal working conditions, the expected service life will be less.

TABLE 14.6 Estimation of Service Life and Annual Maintenance and Repair Costs of Well and Pump Components

Components	Expected service life		Annual maintenance and repair, % of initial investment
	Hours of operations	Years	
Masonry wells	—	50-70	0.2-0.5
Tube well screen and casing (mild steel)	—	20-30	0.5-1.5
Pump house and foundation	—	40-50	0.5-1.5
Bowls of turbine pump (about 50% of the cost of the pump unit)	16,000-20,000	8-10	5-7
Columns of turbine pump	32,000-40,000	16-20	3-5
Centrifugal pump	32,000-50,000	15-25	3-5
Gear head	30,000-36,000	14-20	5-7
V-belt	6,000	3	5-7
Flat belt (leather)	20,000	10	5-7
Electric motor	50,000-70,000	25-35	1.5-2.5
Diesel engine	28,000	15	5-8
Petrol engine	14,000-18,000	8-12	5-10
Galvanized iron pipes	—	20-40	1-2
Portable aluminium pipes	—	15	2-4
Plastic pipes (underground)	—	20-40	1.5-2.5
Concrete and asbestos cement pipes	—	20-40	1-1.5
Hydrants	—	20-40	1-2
Water meters	—	20	2-4
Sprinkler nozzles	—	5-10	2-3
Fittings of portable pipes	—	15	2-3

In addition to interest on investment and depreciation, the annual fixed costs may include taxes, insurance (if applicable) and the amount charged for providing electrical connection. If the electrical connection charges are paid in a lump sum, the annualised cost may be worked out as described above assuming an expected service life of about 25 years. If the charges are to be paid annually, the same are to be added to the annualised investment cost to arrive at the annual fixed cost.

Variable Costs Variable costs include the cost of power/fuel (electricity/diesel/petrol), cost of lubricants, labour charges for operating the pumping set, and the expenditure on repairs and maintenance of the equipment and accessories. The cost of power is often the most important component in variable cost. The usual practice is to calculate the requirement of energy per hour of operation from the known discharge rate of the pumping plant, total operating head and its overall efficiency. The requirement of power is expressed in kilowatt-hours per hour for electricity, and litres of diesel or gasoline per hour of consumption. The input horse power required per hour of operation of a single unit is estimated as follows:

$$\text{Horse power} = \frac{Q \times H}{76 \times \eta} \tag{14.10}$$

where, Q = discharge rate of pumping plant, l/s
H = total head, m
η = overall efficiency of the pumping plant, fraction

In case of pumps connected in series, like multi-stage turbine pumps or booster pumps,

$$\text{Horse power} = \frac{Q(H_1 + H_2 + \ldots + H_n)}{76 \times \eta'} \tag{14.11}$$

where, Q = discharge rate of each pump or pump stage connected in series, l/s
H = total head of each pump, m (The subscripts 1 to n indicate the number of pumps or stages of the pump connected in series)
η' = combined efficiency of all the pumps or pump stages

Input power required for a pump connected in parallel:

$$\text{Horse power} = \frac{(Q_1 + Q_2 + \ldots + Q_n)\, H}{76 \times \eta'} \tag{14.12}$$

where, Q = Discharge rate of each pump, l/s (The subscripts 1 to n indicate the number of pumps connected in parallel)
H = total head of each pump, *m*
η' = overall efficiency of the pump connected in parallel, fraction

Electric motors. Efficiencies of electric motors may be obtained from the performance data supplied by the manufacturers. Motor efficiencies usually vary from 75 to 90 per cent. The energy consumption in kilowatt of an electric motor is computed as follows:

$$\text{Energy consumption} = \frac{\text{Brake horse power}}{\text{Motor efficiency}} \times 0.746$$

Engines. A realistic estimate of the rate of fuel consumption for a given engine can be made if the manufacturer's fuel-consumption curve for that engine is available. The rate of fuel consumption of diesel engines, which are commonly used in irrigation pumping, vary from 0.21 to 0.29 l/bhp-h. An average value of 0.23 l/bhp-h, can be assumed in the absence of better data.

The demand of electrical power for hourly operation is multiplied by the annual hours of operation to arrive at the total annual energy consumption. The annual power cost is determined by multiplying the annual energy demand by the prevailing cost per unit of electrical energy. In case of diesel or petrol engines, the cost of fuel is computed as follows:

Fuel consumption per hour of operation

$$= \text{BHP} \times (\text{Specific fuel consumption}) \times (\text{Cost of fuel per litre})$$

The cost of labour required for the operation of the pumping plant is expressed as the cost per hour of operation, from which the annual cost of labour is computed. The consumption of lubricating oil is usually assumed to be 4.5 1 per 1000 bhp-h. Many manufacturers provide values for the consumption of lubricants of their products. From the cost of lubricants per hour of operation, the annual cost of lubricants is computed.

The repair and maintenance costs may be assumed as per the norms given in Table 14.6, or an average value may be assumed based on practical experience or field evaluation studies.

EXAMPLE 14.3 The water horse power of a centrifugal pump installed in an open well and operated by a direct-coupled 3-phase electric motor is 2.3. The efficiencies of the pump and electric motor are 68 per cent and 76 per cent, respectively. The pump is operated for a total of 2600 hours in 210 days a year. Estimate the annual cost of operating the pump. The cost of the pump and the motor are Rs. 2400 and Rs. 6600 respectively. The total cost of the suction and discharge pipe, pipe fittings, foot valve and strainer amounts to Rs. 2850. The cost of electrical accessories including starter, switch and wiring is Rs. 2460. The cost of electricity is rupees 1.20 per unit. The prevailing interest rate is 8 per cent. The salvage value of pump and motor may be assumed to be Rs. 100 and Rs. 300, respectively. The salvage value of other items is negligible. The time spent by the operator on pumping set is 1 hour daily. The wages of operator is Rs. 60 per day, including his other duties.

Solution

Fixed Costs

1. Annual interest cost $\dfrac{(14310 - 400)}{2 \times 100} \times 8$ = Rs. 556.40
2. Depreciation
   (a) Pump $= \dfrac{2400 - 100}{16}$ = Rs. 143.75
   (b) Motor $= \dfrac{6600 - 300}{25}$ = Rs. 252.00
   (c) Pipe and fittings $= \dfrac{2850 - 0}{25}$ = Rs. 114.00
   (d) Electrical accessories $= \dfrac{2460 - 0}{25}$ = Rs. 98.40
   Total = Rs. 608.15
   Total fixed cost = Rs. 556.40 + Rs.608.15 = Rs. 1164.55

Operating Costs

1. Annual energy consumption $= \dfrac{2.3}{0.68 \times 0.76} \times 0.746 \times 2600$
   = 8632 kWh
2. Cost of electrical energy $= 8632 \times 1.20$ = Rs. 10358.40
3. Pump maintenance and repairs $= 2400 \times \dfrac{4}{100}$ = Rs. 96.00
4. Operator's wages $= \dfrac{1}{8} \times 210 \times 60$ = Rs. 1575.00

   Total operating cost = Rs. 12029.40
   Total annual cost of operation = Fixed cost + Operating cost
   = Rs. 13193.95

Annual Benefit

The annual benefit on account of project implementation is computed for the period of analysis, to carry out the benefit-cost analysis. Benefits from irrigation projects may be either direct or indirect. The main direct benefit is the increase in the value of the crops—its full value under the arid conditions (where no crop can be grown without irrigation) or its additional value, compared with rainfed agriculture (where some crop can be produced without irrigation). The value of the crop is its market price of the produce. Sometimes, irrigation may influence the value of unit quantity of the produce by improving its quality or by providing off-season vegetables, fruits or flowers. In evaluating the benefits, the subsidies and government control of price should be taken into account.

Indirect benefits of irrigation-based projects on wells and pumps include the increase in actual crop area by producing more than one crop per year on the same land. Social and economic benefits include the increase in employment potential and an overall increase in the standard of living. In many cases, projects on wells and pumps intended primarily for irrigation also serve as source for domestic water supply system. These benefits, though indirect, are quantified and included in the benefit-cost analysis. Other indirect benefits include the raising of crops of export value and the resulting foreign exchange earnings and attainment of self sufficiency in food and fibre production.

Salvage value, though not a benefit of the project, is added as a benefit in the analysis. It is the market value of project assets at the end of the economic service period. It includes the sale value of the equipment and material and the value of the pump house.

14.3.5 Collection of Field Data for Project Evaluation

Wells and pumps projects are mainly executed for irrigation or domestic water supply. Investments in the former are much higher than the latter. The various types of data required for an irrigation project include irrigation potential of the project, cropping intensity, cropping pattern, crop yields, value of gross produce and cost of cultivation. In case of domestic water supply, they include the number of households served, population (in age groups), animals, community institutions and the per capita requirement of water for each category of users.

Irrigation Potential

The irrigation potential is estimated from the total quantity of water available from the project and the irrigation requirements of crops for an assumed farming system. A model cropping pattern for a farm is assumed on the basis of the data on climate, soil type, requirements and habits of farmers, and a favourable economic return. The water requirements of crops during the winter season (*rabi*) and monsoon season (*kharif*) are computed on a unit-area basis. The capacity of the well divided by the irrigation requirements of crops gives the area which can be irrigated.

Crop Yield and Value of Gross Product

The average yield of each crop is assumed on the basis of studies carried out by various agencies. The value of the gross produce for the whole year is calculated from the total yield of each crop and its market price. Similarly, for the same block of area to be benefited by the project, the prevailing yield of various crops (under rainfed and irrigated agriculture conditions) is estimated. The gross value is calculated with a view to determining the increase in total income, as a result of the implementation of the project.

Cost of Cultivation

The total cost of cultivation per unit net-cropped area benefited by the investment, as well as the cost of cultivation for the pre-investment period are computed. The increase in the cost of cultivation per unit area, on account of project implementation, is computed. The cost of cultivation will include variable costs for fertilizers and manures, seeds and seedlings, pesticide, wages, cost of operation of tractors and other machinery, maintenance of draught animals, and miscellaneous minor costs.

Incremental Income

The incremental income is computed by subtracting the net farm income before investment on the project from the net farm income after investment. The annual incremental income provides the annual benefit.

In case of projects for drinking water supply, the incremental income may be computed by comparing the existing system with the improved system to be implemented. The benefit for each year of project life is calculated. The incremental benefit so calculated is converted to the present worth value.

14.3.6 Cost Escalation

In actual practice, the fixed and variable costs associated with wells and pumps projects often increase during the project period. This may affect the initial design and selection of various items of the project. The projected rate of escalation during the period of analysis can be incorporated in the present worth and annual cost values. The escalated present worth at the end of n years of the life of a component is given by the following relationship:

$$P_{wf(e)} = \frac{(1+e)^n}{(1+i)^n} \tag{14.13}$$

where,
$P_{wf(e)}$ = escalated present worth factor, fraction
e = annual rate of escalation, fraction
i = annual interest rate, fraction
n = expected life of the component, years

Equation (14.13) can be used to evaluate the effect of escalation on fixed cost items such as replacement of the pump. The present worth value incorporating the effect of cost escalation can be obtained using the following relationship:

$$PW\,(e) = PW \times P_{wf(e)} \tag{14.14}$$

Where, $PW\,(e)$ = present worth cost, incorporating the effect of escalation cost, Rs.

The annual cost value can be adjusted for the cost of escalation by multiplying its value with the annual cost escalation factor (Pearson, 1974).

$$A_{cf(e)} = \frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)} \times \frac{i}{(1+i)^n - 1} \tag{14.15}$$

for $e \# i$

and $$AC(e) = A_{cf(e)} \times AC \tag{14.16}$$

Where, $AC\ (e)$ = annual cost, incorporating the effect of cost escalation, Rs.
$A_{cf(e)}$ = annual cost escalation factor, fraction

Example 14.4 A centrifugal pump of initial cost Rs 3000 is to be replaced after 7 years, during a project period of 14 years. What would be the present worth value of replacement if the rate of interest is 10 per cent and the project escalation rate of costs is 8 per cent?

Solution
The present worth value, incorporating the effect of cost escalation, is given by Eq. (14.14)
In this case,

$$PW = \text{Rs } 3000$$

$$P_{wf(e)} = \frac{(1+0.08)^7}{(1+0.10)^7} = \frac{(1.08)^7}{(1.10)^7}$$

$$= 0.88$$

∴ The present worth value, $PW\ (e) = 3000 \times 0.88 = \text{Rs } 2640$

Example 14.5 The estimated cost of energy per year for a community drinking water supply project is Rs. 10,000, based on the current energy cost. However, the cost is likely to escalate at a rate of 8 per cent per year for the 25-year project period. What would be the equivalent energy cost which should be considered for economic analysis when the rate of interest on capital investment is 10 per cent?

Solution
The annual cost, incorporating the effect of escalation $AC\ (e)$, is given by Eq. (14.16).

$$AC\ (e) = A_{cf(e)} \times AC$$

In this case,

$$A_{cf(e)} = \frac{(1+0.08)^{25} - (1+0.10)^{25}}{(1+0.08) - (1+0.10)} \times \frac{0.10}{(1+0.10)^{25} - 1}$$

$$= \frac{6.85 - 10.83}{-0.02} \times \frac{0.10}{10.83 - 1}$$

$$= 2.02 \text{ and } AC = \text{Rs } 10000$$

Therefore, equivalent energy cost

$$= 10000 \times 2.02 = \text{Rs } 20200.00$$

14.3.7 Case Studies on the Application of Discounting Techniques

Each of the discounting techniques described above, when applied correctly, would give the desired results. However, each method has advantages and disadvantages associated with the ease of calculation and understanding of the results. The present-worth technique is simple and easy to use. However, large numbers are involved, which could lead to numerical errors. The internal rate of return has the advantage that it does not require a pre-selected discount rate, but ambiguous answers are sometimes obtained because of dual solutions. The benefit-cost ratio method is almost universally used. However, its use without applying the required incremental benefit cost analysis can lead to serious errors. The annual benefit-cost method has the same advantages and disadvantages, as the present worth method, but is commonly accepted in the analysis of wells and pumps projects because the project authorities are usually accustomed to thinking in terms of annual cost and benefit analysis.

EXAMPLE 14.6 A proposal has been received for financing a tube well project (cavity wells) in a certain area. The command area of a tube well is 3 ha. The annual benefit for introducing the irrigation scheme is Rs. 40,000 per tube well. The estimated cost of installation of a cavity tube well (diesel engine as well as electric motor operated) is given in Table 14.7. The average life of the tube well, along with its components, may be taken to be 20 years, except for the diesel engine pumping set which will have to be replaced after 10 years. The residual cost at the end of 20 years may be considered negligible for the purpose of analysis. Determine the benefit cost ratio for the tube wells operated by pumps driven by engines as well as electric motors.

The rate of interest is 10 per cent and the cost of escalation may be assumed at a rate of 7 per cent. The tube well would be operated for 1000 hours annually. The cost of diesel oil and electricity are Rs. 15 per litre and Rs. 2.00 per kWh, respectively.

Solution

The details of the initial investment on the installation of a cavity tube well are given in Table 14.7. The annual benefits as a result of tubewell installation are Rs. 40,000 per tube well. The annual cost for diesel-engine and electric-motor operated pumping sets will have to be estimated to determine the benefit-cost ratios.

TABLE 14.7 Computation of Initial Investment on a Cavity Tube well in Example 14.6

Particulars	Tube well equipped with diesel engine operated pump	Tube well equipped with electric motor driven pump
Average depth of water table	12 m	12 m
Average depth of boring	30 m	30 m
Cost of construction of well:		
(a) Digging a pit 10 m deep at Rs. 60/m	Rs. 600	Rs. 600
(b) Boring charges (including labour and transportation charges) @ Rs 40/m	Rs. 1200	Rs. 1200
(c) Cost of cavity development, pipe and other materials	Rs. 1000	Rs. 1000
(d) Cost of 8 sockets @ Rs. 20 each, including one blind socket	Rs. 160	Rs. 160
(e) Cost of 10 cm dia, suction pipe @ Rs. 120/m, for 30 metre length	Rs. 3600	Rs. 3600

(*Contd.*)

TABLE 14.7 (*Contd.*)

Particulars	Tube well equipped with diesel engine operated pump	Tube well equipped with electric motor driven pump
(f) Cost of 10 cm dia, delivery pipe (light weight) 12 m (10 + 2) @ Rs. 80/m	Rs. 960	Rs. 960
Sub total	**Rs. 7520**	**Rs. 7520**
Cost of 7.5 hp diesel engine/5 hp electric motor, including centrifugal pump	Rs. 14000	Rs. 8000
Cost of reflux valve, rubber packing, etc.	Rs. 200	Rs. 200
Other expenses for electrical-installation, including starters, switches and cables	–	Rs. 3450
Cost of construction of pump house, delivery tank and pump foundation	Rs. 7000	Rs. 7000
Cost of obtaining electrical connection	–	Rs. 500
Total	**Rs. 28720**	**Rs. 26670**

Annual Cost of Tube Well Operated by Diesel Engine Driven Pump Set

This would include the fixed costs and variable costs.

Fixed costs. The fixed cost is obtained from the initial investment multiplied by capital recovery factor. The expected life of the project is 20 years. The diesel engine will have to be replaced after 10 years. Therefore, the replacement cost of the diesel engine pumping set will have to be added to the initial cost. The present cost of replacement is given by Eq. (14.14).

$$PW\,(e) = PW \times P_{wf(e)}$$

$$= 14000 \times \frac{(1+0.07)^{10}}{(1+0.10)^{10}}$$

$$= 14000 \times \frac{1.967}{2.594} = \text{Rs. } 10616$$

∴ Present cost for a cavity well equipped with diesel engine operated pumping set = 28720 + 10616 = Rs. 39336

The capital recovery factor is defined by Eq. (14.8).

$$C_{rf} = \frac{r(1+r)^n}{(1+r)^n - 1} = \frac{0.10(1+0.10)^{20}}{(1+0.10)^{20} - 1}$$

$$= 0.11746$$

∴ Fixed cost = 39336 × 0.11746 = Rs. 4620.40

Annual Variable Cost for Cavity Tube Well Operated by Diesel Engine Driven Pump Set

1.	Average fuel consumption @ 0.25 litre per hp per hour @ Rs. 15 per litre for 1000 hours of operation	Rs. 28125
2.	Lubricating oil and grease @ 4 litres per 1000 hours per hp @ Rs. 30 per litre	Rs. 900
3.	Maintenance and repair cost @ 3 per cent of initial investment, excluding the cost of bore, i.e. on Rs. 28720 – 7520 i.e. Rs. 21200	Rs. 636
4.	Labour charges @ Rs. 100 per month	Rs. 1200
	Total	Rs. 30861

Total annual cost = 4620.40 + 30861.00 = Rs. 35481.40

∴ Benefit-cost ratio of tube wells equipped with diesel engine driven pump sets

$$= \frac{40000}{35481.4} = 1.13$$

Annual Cost for a Cavity Tube Well Operated by Electric Motor Driven Pump Set

This will include fixed cost and variable cost.

Fixed Costs $\quad PW \times C_{rf}$

26670×0.11746

= Rs 3132.65

Variable Cost. Assuming that the motor is fully loaded, the operating cost for 1000 hours per year for a motor of 5 hp @ Rs. 2.00 per kWh

$$= \frac{5 \times 746 \times 1000 \times 2.00}{1000} = \text{Rs. } 7460.00$$

Repair and maintenance cost @ 3 per cent of initial investment, excluding the cost of bore, i.e. on (Rs 26670 – 7520) = Rs 574.50

Labour charges @ Rs 100 per month = Rs 1200.00

Total = Rs 9234.50

∴ Annual cost for electric motor operated well

= Rs 3132.65 + 9234.50

= Rs 12367.15

$$\frac{B}{C} = \frac{40000}{12367.15}$$

$$= 3.23$$

Example 14.7 It is proposed to install 400 shallow tube wells in a project area. The various particulars of the project area are given below:

1.	Culturable area	= 52887 ha
2.	Specific yield	= 12.5%
3.	Average seasonal fluctuation of water level (1992-1999)	= 0.91 m
4.	Monsoon rainfall (based on 7 years data)	= 427.24 mm
5.	77 years average annual monsoon rainfall	= 409.89 mm
6.	77 years average annual non-monsoon rainfall	= 32.11 mm
7.	State tube wells (existing)	= 15
8.	Private tube wells (existing)	= 1000
9.	Masonry wells with Persian wheel (existing)	= 148
10.	Masonry wells with manually operated water lifts (existing)	= 148
11.	Main canals with average wetted perimeter of 35 m	= 10 km
12.	Distributory canals with average wetted perimeter of 10 m	= 40 km
13.	Minor canals with average wetted perimeter of 3 m	= 18.5 km
14.	Average depth of water table below ground level	= 8 m

Carry out the techno-economic evaluation of the project and prepare a report with a view to determining the economic viability and technical feasibility of the project.

The additional data required as regards the topography of the project area, existing and projected cropping patterns, average yield of crops, hydrogeology, unit draft to various types of wells, seepage rate, etc. are available in the project file. Canal water released at the outlet is 6294 ha-m and 3000 ha-m during non-monsoon and monsoon periods, respectively. Suitable assumptions may be made for any other missing data.

Solution

The project file presents the characteristics of the project area, occurrence of ground water, present quantum of development, existing number of various types of wells and their respective annual draft, ground water balance, benefit, detailed economic analysis and recommendations on the credit worthiness of the project.

Climate and Rainfall. The climate of the area is sub-tropical with three typical seasons, namely, winter (October-February), summer (March-June) and rainy season (July-September). A maximum temperature of about 40°C is common from May to August. The minimum temperature recorded during the winter months from December to February is 3°C. Seventy per cent of the average annual rainfall occurs from June to September. The normal monsoon rainfall, based on 77 years record, is 409.89 mm, while the average of the past 7 years is 427.24 mm.

Soils of Project Area. The soils of the area form part of the Indo-Gangetic plain and are alluvial in nature and sandy loam to clay in texture. They are neutral in chemical reaction. The soils are fairly rich in phosphorus and poor in nitrogen and potash. They are permeable and have good internal drainage.

Cropping Pattern. The principal crops of the project area are maize in the monsoon (*kharif*), wheat in winter (*rabi*) and the long duration crop of sugarcane. The common crop rotations followed are as follows:

Maize-Wheat

Maize-Sugarcane (two years)

Sorghum (fodder)-Wheat

Maize-Fodder (oat + peas/berseem)

Maize-Potato-Wheat (1 year)

Average Yield of Crops. The average yield of crops under rainfed and irrigated agriculture is given in Table 14.8.

TABLE 14.8 Average Yield of Crops in the Project Area of Example 14.8

Group	Average yield, qtl/ha	
	Under rainfed agriculture	Under irrigated agriculture
Monsoon crop (*kharif*)		
Maize	12.5	25.0
Pearl millet (*bajra*)	7.5	—
Cotton	7.5	12.5
Paddy	—	35.0
Sugarcane	—	500.0
Winter Crop (rabi)		
Sugarcane	—	
Wheat	15.0	35.0
Potato	—	200.0
Gram	7.5	—

Availability of Equipment/Material and Personnel. The Department of Minor Irrigation of the State Government, which is equipped with a variety of drilling equipment, undertakes the work of tube well boring and pump installation. In addition, there are a large number of private dealers operating in the project area who undertake the work of boring tube wells and installing pump sets. Materials such as pipes, strainers, electric motors, diesel engines and pumps of standard make are easily available in the open market. Adequate skilled labour is available in the project area.

Facilities for Repair and Maintenance of Equipment. Adequate servicing facilities are available to the farmers from private dealers. At present they depute their mechanics to fields immediately on request, and extend prompt servicing facilities.

Supporting Agricultural Operations. The farmers in the area have already adopted high-yielding crop varieties. The state department of agriculture and the state agricultural university provide technical staff to advise the farmers.

Marketing Facilities. Regulated marketing arrangements are in existence in project areas. As such, no difficulty is likely to be experienced by the farmers in disposing of the additional produce generated by the scheme.

Hydrogeology. Exploratory drilling carried down to a depth of 400 metres had not encountered any bed rock. The alluvial complex consists principally of fine-to-medium sand and clay. Beds of gravel of a very coarse sand are also available. One aquifer of about 16 m thickness is available within a depth of 30 m and the other of 30 m between 30 and 100 m depth. The first aquifer has been developed extensively by private tube well owners. The average depth of shallow tube wells is 30 m. Because of non-availability of the required strength and thickness of the impervious layer required for cavity wells, only strainer wells could be installed in the area.

Pumping-Test Data. During the course of hydrological investigations, the performance of the existing wells was observed. The average discharge of shallow tube wells was 9 l/s for a drawdown of about

1.5 m. The average depth of ground water was 4 m below ground level. Tests carried out by the State Ground Water Cell of the State Department of Agriculture revealed that the radius of influence of the well, for a pumping period of 2 hours, was 200 m.

Annual Ground Water Recharge

1. *Monsoon Period.* The ground water recharge during the monsoon period is obtained from Eq. (14.2).

$$R_{rf} = h.Sy.A. + D_G - R_c - R_{gw} - R_{sw} - R_t - R_{wc}$$

Where,

R_{rf} = Recharge from rainfall during pre-and post-monsoon periods, ha-m

h.Sy.A = Water level fluctuation × Specific yield × Area

= $0.91 \times 0.125 \times 52887 = 6015.90$ ha-m

D_G = Gross ground water draft during monsoon

The draft during the monsoon period, as a result of pumping from the wells in the area, is presented in Table 14.9. From Table 14.9,

D_G = 984 ha-m

R_c = recharge from canal seepage during monsoon, ha-m

TABLE 14.9 Number of Existing Wells of Different Types and Their Annual Draft in Example 14.8

Type of well	Number	Unit draft		Total annual draft	
		Monsoon period, ha-m	Non-Monsoon period, ha-m	Monsoon period, ha-m	Non-Monsoon period, ha-m
State tube wells	15	14.0	32.0	210	480
Private shallow tube wells	1000	0.7	1.3	700	1300
Masonry wells with Persian wheels	148	0.3	0.6	44	89
Masonry wells with manually operated water lifts	148	0.2	0.4	30	59
Total				984	1928

The seepage from the canal network (considering the seepage rate to be 20 ha-m per day/million square metre of wetted area of the canal) is given in Table 14.10. From Table 14.10.

R_c = 1391.5 ha-m say 1392 ha-m

R_{gw} = recharge from ground water irrigation during the monsoon period (25 per cent of the ground water draft during the monsoon period, Table 14.2)

$$= \frac{25}{100} \times 984 = 246.00 \text{ ha-m}$$

R_{sw} = Recharge from surface water irrigation during monsoon (30% of the water delivered at outlet for application in the field, Table 14.2)

$$= \frac{30}{100} \times 3000 = 900 \text{ ha-m}$$

R_t, R_{wc} = 0 (since there is no storage tank and water harvesting structure in the project area)

Total recharge from sources other than rainfall during monsoon = 1392 + 246 + 900 = 2538 ha-m

Rainfall recharge during monsoon period

= 6015.90 + 984 – 2538 = 4461.9 ha-m

Rainfall recharge corresponding to normal monsoon rainfall = $\frac{4461.9}{427.24} \times 409.89 = 4280.7$

say 4281 ha-m

If more than one pair of rainfall and recharge data are available, the rainfall recharge corresponding to normal season rainfall can be calculated for each pair, and an average of these values can be then obtained.

Table 14.10 Data on Recharge from Canal Systems in Example 14.8

Type of canal	**Length, Km**	**Average annual running days**		**Average wetted perimeter, m**	**Total seepage**	
		Non-monsoon period	**Monsoon period**		**Monsoon period, ha-m**	**Non-monsoon period, ha-m**
Main canal	10	230	115	35	805	1610
Distributory canals	40	130	65	10	520	1040
Minor canals	18.5	120	60	3	66.5	133
Total					1391.5	2783

Rainfall recharge by rainfall infiltration factor = $52887 \times \frac{427.24}{1000} \times \frac{22}{100} = 4970.99$

(Refer Table 14.1)

say 4971 ha-m

Per cent difference between rainfall recharge by water table fluctuation method and rainfall infiltration factor method = $\frac{4281 - 4971}{4971} \times 100 = -13.8$

Since, per cent difference lie between –20 per cent to +20 per cent, the rainfall recharge for normal monsoon is taken as the value estimated by the water table fluctuation method = 4281 ha-m

2. Non-Monsoon Period. The ground water recharge during the non-monsoon period will include the recharge from the canal system and from recycled irrigation water, including ground water.

(i) Recharge from Non-Monsoon Rainfall. Since the normal rainfall during non-monsoon period is less than 10 per cent of normal annual rainfall, the recharge from non-monsoon rainfall is taken as zero.

(ii) Recharge on account of Seepage from Canal Network. The canals in the area are unlined. Seepage loss has been taken at 20 ha-m per day per million square metres of wetted area of the canal. The length of the canals and the number of days of operation during the non-monsoon period

are given in Table 14.10. The ground water recharge, as a result of seepage from the canal network, amounts to 2783 ha-m.

(iii) Recharge from Irrigation Water (Surface Water). From the canal operation period, it was observed that the total quantity of water released from the outlet during the non-monsoon period was 6294 ha-m. Out of which 30 per cent is assumed to percolate below the crop root zone, as the water courses are unlined and surface irrigation is practised. Hence, the recharge from this component is estimated as

$$6294 \times \frac{30}{100} = 1888 \text{ ha-m}$$

(iv) Recharge from Irrigation Water (Ground Water). Considering the deep percolation loss to be 25 per cent of the total ground water draft, the ground water recharge works out to be 1928 × 25/100 = 482 ha-m.

The total ground water recharge during the non-monsoon season is estimated as follows:

1.	Canal seepage	= 2783 ha-m
2.	Deep percolation from canal irrigated fields	= 1888 ha-m
3.	Deep percolation from ground water irrigated fields	= 482 ha-m
		= 5153 ha-m
	∴ *Total annual ground water recharge*	= 4281 + 5153 = 9434 ha-m

Annual Ground Water Draft

From Table 14.9, the annual ground water draft is

$$984 + 1928 = 2912 \text{ ha-m}$$

Utilizable Annual Ground Water Recharge. Assuming that 15 per cent of the total annual ground water recharge would be required for industrial and domestic use, the utilizable annual ground water recharge for irrigation is

$$9434 \times 0.85 = 8018.9 \quad \text{say} \quad 8019 \text{ ha-m}$$

∴ The ground water balance for development through institutional financing = 8019 – 2912 = 5107 ha-m

Against this, a programme of 400 shallow tube wells with an anticipated annual draft of 1000 ha-m is proposed in the area. Thus, the total draft will be 2912 + 1000 = 3912 ha-m. The level of ground water development will be

$$\frac{3912}{9434} \times 100 = 41.47 \text{ per cent}$$

Design of the Tube Well and Selection of Pumping Equipment

The detailed design of the tube well and the procedure for selection of pumping equipment are given in Chs. 4 and 9, respectively. Considering that the discharge capacity is not limited from the view of aquifer characteristics, it is decided on the basis of irrigation requirements of crops. These principal crops being grown under irrigated conditions are maize, sugarcane and wheat. The command area of the shallow tube well varies from 2.5 to 3.5 ha. To estimate the irrigation requirements of crops, a model farm of 3 ha is taken (Table 14.11).

The irrigation requirement is determined by the relationship expressed in Eq. (9.23)

$$Q = \frac{27.78}{T} \sum_{n=1}^{n} \frac{A_n Y_n}{R_n}$$

The working hours/day is assumed to be 6. The water requirements for different seasons is estimated as follows:

TABLE 14.11 Cropping Pattern and Water Requirements of the 3 ha Model Farm Excluding Effective Rainfall in Example 14.8

Seasons and crop	Area, ha	Irrigation Intervals, days	Depth of irrigation, cm
1. Monsoon season crop			
(a) Maize	1.5	24	6
(b) Cotton	0.5	20	7
(c) Paddy	0.5	3	7
2. Winter Season			
(a) Wheat	2.5	30	7
(b) Potato	0.5	10	8

Monsoon season crop:

$$\text{Water requirement} = 27.78 \left(\frac{1.5 \times 6}{24 \times 6} + \frac{0.5 \times 7}{20 \times 6} + \frac{0.5 \times 7}{3 \times 6} \right)$$

$$= 27.78\ (0.0625 + 0.0292 + 0.1944)$$

$$= 27.78 \times 0.2861$$

$$= 7.94 \text{ say } 8 \text{ l/s}$$

Winter crop

$$\text{Water requirement} = 27.78 \left(\frac{2.5 \times 7}{30 \times 6} + \frac{0.5 \times 8}{10 \times 6} \right)$$

$$= 27.78\ (0.972 + 0.0667)$$

$$= 27.78 \times 0.1639$$

$$= 4.55 \text{ l/s}$$

The maximum demand for irrigation water to meet the crop water requirement is about 8.00 l/s, which is during the monsoon crop season.

Based on the strata chart and the capacity required, the various components of a tube well, along with their initial investment, are given in Table 14.12.

Annual cost

The annual cost analysis is made on the assumption that the average life of various components of the tube well and pump set is 20 years. The cost of replacement of the flat belt and other minor accessories are considered negligible in the analysis. The rate of interest has been assumed to be 10 per cent.
Annualised investment cost

$$AC = PW \times C_{rf}$$

$$PW = \text{Rs. } 16700$$

From Eq. (14.8)

$$C_{rf} = \frac{r(1+r)^n}{(1+r)^n - 1} = \frac{0.10\,(1+0.10)^{20}}{(1+0.10)^{20} - 1}$$

$$= 0.11746$$

$$\therefore \quad AC = 16700 \times 0.11746 = \text{Rs } 1961.58$$

Other fixed costs. The charges for providing the electric connection is Rs. 4000. The rate of interest is 10%.

$$\text{Fixed cost} = PW \times C_{rf}$$

$$= 4000 \times 0.11746$$

$$= \text{Rs. } 469.84$$

Total annual fixed cost $= \text{Rs. } 1961.58 + \text{Rs. } 469.84$

$$= \text{Rs. } 2431.42$$

TABLE 14.12 Details of the Design of the Tube well in Example 14.8

Items	**Quantity**	**Initial investment Rs.**
Depth of boring	30 m	1800
Length of agricultural strainer	15 m	1500
Length of blind pipe and delivery pipe (100 mm dia)	15 m	1500
HP of motor	3 HP	3000
Shingle for shrouding	Lump sum	400
Depth of pit for installation of centrifugal pump	2 m	1600
Length of flat belt	6 m	200
Standard elbow	1	200
Reflux value	1	400
Centrifugal pump	1	2000
Bail plug	1	100
Pump house and delivery tank	1	4000
Total		Rs. 16700

Annual Variable Cost. The annual variable cost includes cost of power and labour for operating the pumping set and the cost of repair and maintenance. The repair and maintenance costs, in terms of percentage of the initial investment, is presented in Table 14.6. An average value of 3 per cent is assumed in this case. The cost of power is one of the most dominating components of variable cost. Usually, the requirement of input power is calculated from the discharge capacity, total operating head and overall efficiency of the pumping set. The requirement of power per hour of operation multiplied by the total number of hours of operation during a year gives the total power requirement. The yearly operational cost is computed, using the rate per unit of electric power.

However, in this case, the electricity charges are recovered from the farmers at Rs 200 per horse power of motor per month, and the same is considered for the analysis. The annual variable cost per well is computed, as follows:

1. Annual cost of power at Rs. 200 per hp per month = $200 \times 3 \times 12$ = Rs 7200.00
2. Repair and maintenance cost at 3 per cent on Rs 16700.00 = Rs. 501.00
3. Operation charges at Rs. 200 per month = Rs. 2400.00

Total = Rs. 10101.00

∴ Annual cost = Rs. 2431.42 + Rs. 10101.00 = Rs. 12532.42

Annual Benefits

The annual benefit is the yearly incremental income, which is computed by subtracting the pre-project net farm income from the post-project net farm income. The net income under rainfed agriculture (pre-project period) and under irrigated agriculture (post-project period) are given in Tables 14.13 and 14.14, respectively. The average yields of crops in both situations have been assumed on the basis of data collected from the project area. The cost of cultivation has been obtained from the State Department of Agriculture. New crops have been suggested under irrigation conditions. The returns from farm produce are assumed on the basis of prevailing market rates.

The income from a 3-hectare farm is Rs. 22102.5 (Table 14.13) and Rs. 40550.00 (Table 14.14) under rainfed (pre-project) and irrigated conditions (post-project), respectively. Thus, the annual incremental income is Rs. 18447.50.

TABLE 14.13 Economics of Rainfed 3-ha farm, (Example 14.8)

Crop	**Area ha**	**Yield qtls/ha**	**Total production qtl**	**Price per qtl Rs.**	**Value of farm produce**			**Cost of cultivation/ha Rs.**	**Total cost of cultivation Rs.**	**Income Rs.**
					Grain Rs.	**Fodder Rs.**	**Total Rs.**			
Monsoon crop (*Kharif*)										
Pearl millet (Bajra)	1.5	7.5	11.25	330	3712.5	300.00	4012.50	1800.00	2700.00	1312.50
Maize	1.0	12.5	12.50	360	4500.00	900.00	5400.00	1800.00	1800.00	3600.00
Cotton	0.5	7.5	3.75	900	3375.00	–	3375.00	2400.00	1200.00	2175.00
Winter crop (*rabi*)										
Wheat	2.0	15.0	30.0	450	13500.00	1350.00	14850.00	1500.00	3000.00	11850.00
Gram	1.0	7.5	7.5	582	4365.00	–	4365.00	1200.00	1200.00	3165.00
Total										22102.5

Annual Benefit-Cost Ratio

The ratio of the annualised benefit to the annualised cost is known as the benefit-cost ratio. Hence,

$$\frac{B}{C} = \frac{18447.5}{12532.42} = 1.47$$

Present Worth

The present worth of the project, as defined by Eq. (14.5)

$$PW = -K + B'\left(\frac{P}{A}, i\%, n\right)$$

In this case, K = Rs. 16700 + Rs. 4000 = Rs. 20700.00

And B' = Rs. 18447.5 – Rs. 12532.42 = Rs. 5915.08

$$\frac{P}{A} = \frac{1}{C_{rf}} = \frac{1}{0.11746} = 8.51$$

TABLE 14.14 Economics of irrigated 3-ha Farm (Example 14.8)

Crop	Area ha	Yield qtls /ha	Total produ-ction qtl	Price per qtl Rs.	Value of farm produce			Cost of cultiva-tion/ha Rs.	Total cost of cultiva-tion Rs.	Income Rs.
					Grain Rs.	Fodder Rs.	Total Rs.			
Monsoon crop (*Kharif*)										
Maize	1.5	25.00	37.50	360	13500.00	3000.00	16500.00	9000.00	13500.00	3000.00
Cotton	0.5	12.50	6.25	900	5625.00	–	5625.00	6000.00	3100.00	2525.00
Paddy	0.5	35.00	17.50	360	6300.00	300.00	6600.00	6000.00	3000.00	3600.00
Sugarcane (Feb-March)	0.5	500.00	250.00	63	15750.00	–	15750.00	15000.00	7500.00	8250.00
Winter crop (*rabi*)										
Potato	0.5	200.00	100.00	225	22500.00	–	22500.00	24000.00	12000.00	10500.00
Wheat	2.5	35.00	87.50	450	39375.00	3300.00	42675.00	12000.00	30000.00	12675.00
Total Rs.										40550.00

∴ PW = – 20700 + 5915.08 × 8.51
= Rs 29637.33

Internal Rate of Return

The internal rate of return is defined by Eq. (14.9):

$$\frac{r(1+r)^{20}}{(1+r)^{20}-1} = \frac{B'}{K} = \frac{5915.08}{20700} = 0.285$$

The value r is found by trial and error. Assuming different values of the internal rate of return, the capital recovery factor is calculated. The internal rate of return r which gives the capital recovery factor value close to the given value is chosen. The capital recovery for different values of r are given below:

r	0.25	0.30	0.35	0.40	0.45	0.50
Crf	0.240	0.30	0.35	0.40	0.45	0.50

As calculated above, the internal rate of return is about 28 per cent, as it gives the desired value of the capital recovery factor of 0.285.

Conclusions

The following conclusions can be drawn from the techno-economic evaluation of the project:

1. The proposed project is technically feasible. For a stage of ground water development at 85 per cent of the recoverable recharge, the net ground water balance (after making provision for ground water development from privately financed resources) is 5107 ha-m. The present project is for an anticipated withdrawal of 1000 ha-m. Even after the implementation of the project, the total draft will be only 41.47 per cent of the available net recharge. Hence, the project is safe from the water balance point of view.
2. The project is economically viable because the benefit-cost ratio is as high as 1.47. The internal rate of return is 28 per cent, which is considered a very high value.

Thus, the proposed project for the installation of 400 shallow wells in the project area is technically sound and economically feasible.

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PROBLEMS

14.1 The initial investment on a tube well and pump project is Rs. 6,00,000. The yearly net benefit is Rs. 50,000. Estimate the present worth if the project period is 20 years and the discount rate 10 per cent.

Ans. Rs. 1,74,500.00

14.2 In a tube well and pump project, the initial cost is Rs. 6,00,000. The project period is 20 years. The annual net benefit is Rs. 80,000. Estimate the internal rate of return.

Ans. $r = 12\%$

14.3 A diesel engine, costing Rs. 10,000 initially, is to be replaced after 7 years during a project period of 14 years. What would be the present worth value of replacement if the rate of interest is 10 per cent and the projected escalation rate of costs is 8 per cent.

Ans. PW = Rs 8880.00

14.4 The initial investment on a tubewell is Rs. 10,000. The expected life is 25 years. The rate of interest is 10 per cent. Estimate the annual investment cost.

Ans. AC = Rs 1101.76

SHORT QUESTIONS

I. State True (T) or False (F).

1. The ground water available for development is the difference between annual replenishment and annual draft.
2. The watershed development with associated soil conservation measures increases the recharge to ground water form rainfall.
3. The recharge from rainfall will be more in semi-consolidated sandstone than alluvial areas.
4. In shallow water table areas, the recharge from canal seepage will be more.
5. Greater the depth to water table below ground surface more will be the amount of return flow from irrigated fields.
6. In an influent river the ground water flows toward the river.
7. For estimating ground water recharge, water balance approach is more accurate.
8. Specific yield of sandy alluvium is more than silty alluvium.
9. Water conservation structures do not add to ground water recharge.
10. Rainfall recharge in a particular monsoon season is normalized for the normal monsoon season using average of the monsoon season rainfall for recent 30 years.
11. The recharge from rainfall during non-monsoon period for normal rainfall less than 10 per cent of the normal annual rainfall is taken as zero.
12. Ground water resource in the zone of water level fluctuations is called static ground water resource.
13. In areas where ground water development is more than 100 per cent, but either pre- or post-monsoon ground water level does not show a significant long term decline is categorized as over-exploited.
14. The average annual gross unit draft of various types of ground water structures will be more in hard rock areas.
15. Internal rate of return is defined as the interest rate which will provide the equalization of total cost to benefits.
16. When projects are ranked in order of merit, both internal rate of return and benefit-cost ratio methods results in similar ranking when comparing projects with similar benefit-cost ratios.
17. The fixed costs include depreciation plus interest on investment.
18. Taxes, insurance and the amount charged for providing electrical connection are included in variable costs.
19. In evaluating the benefits, the subsidies and government control of price should be taken into account.
20. Salvage value is added as a benefit in project analysis.

    Ans. True: 1, 2, 5, 7, 8, 10, 11, 15, 16, 17, 19, 20.

II. Select the correct answer.

1. The recharge to ground water due to seepage from canal is 20 ha-m/day/10^6 m^2 of wetted area, which is equivalent to

   (a) 1.8 cumecs/10^6 m^2 of wetted area (b) 2.3 cumecs/10^6 m^2 of wetted area

   (c) 3.0 cumecs/10^6 m^2 of wetted area (d) 3.5 cumecs/10^6 m^2 of wetted area

2. Areas where stage of ground water development is between 90-100 per cent but both pre- and post-monsoon ground water levels shows a significant long term decline are categorized as
   (a) safe areas (b) semi-critical areas
   (c) critical areas (d) over-exploited
3. The indirect benefits form the irrigation-based projects on wells and pumps include
   (a) increase in actual crop area (b) increase in value of the crops
   (c) improving the quality of the crops (d) providing off-season vegetables
4. Fixed costs include
   (a) cost of fuel (b) expenditure on repair and maintenance
   (c) planning and design cost (d) manpower cost
5. If the estimated life of a project is n years, and the rate of interest per annum is r, the capital recovery factor equals
   (a) $[r(1 + r)^n]/ [(1 + r)^n-1]$ (b) $(1 + r)/ [(1 + r)^n - 1]$
   (c) $[r(1 + r)^n]/ [1 - (1 + r)^n]$ (d) $[n(1 + r)^n]/ [(1 + r)^n - 1]$
6. The estimated life of a tubewell is of the order of
   (a) 10 years (b) 20 years
   (c) 30 years (d) 50 years

Ans. 1. (b) 2. (d) 3. (a) 4. (c) 5. (a) 6. (c)

Appendix A

Theis' Well Function $W(u)$, Corresponding to Values of u and $1/u$

n	*N*	I/*u* = *n* *u* = *N*	*n*(1) *N*(–1)	*n*(2) *N*(–2)	*n*(3) *N*(-3)	*n*(4) *N*(–4)	*n*(5) *N*(–5)	*n*(6) *N*(–6)	*n*(7) *N*(–7)	*n*(8) *N*(–8)	*n*(9) *N*(–9)	*n*(10) *N*(–10)
1.000	1.0	*W*(*u*) = 2.194 (–1)	1.823	4.038	6.332	8.633	1.094 (1)	1.324 (1)	1.554 (1)	1.784 (1)	2.015 (1)	2.245 (1)
0.833	1.2	1.584 (–1)	1.660	3.858	6.149	8.451	1.075 (1)	1.306 (1)	1.536 (1)	1.766 (1)	1.996 (1)	2.227 (1)
0.666	1.5	1.000 (–1)	1.465	3.637	5.927	8.228	1.053 (1)	1.283 (1)	1.514 (1)	1.744 (1)	1.974 (1)	2.204 (1)
0.500	2.0	4.890 (–2)	1.223	3.355	5.639	7.940	1.024 (1)	1.255 (1)	1.485 (1)	1.715 (1)	1.945 (1)	2.176 (1)
0.400	2.5	2.491 (–2)	1.044	3.137	5.417	7.717	1.002 (1)	1.232 (1)	1.462 (1)	1.693 (1)	1.923 (1)	2.153 (1)
0.333	3.0	1.305 (–2)	9.057 (–1)	2.959	5.235	7.535	9.837	1.214 (1)	1.444 (1)	1.674 (1)	1.905 (1)	2.135 (8)
0.286	3.5	6.970 (–3)	7.942 (–1)	2.810	5.081	7.381	9.683	1.199 (1)	1.429 (1)	1.659 (1)	1.889 (1)	2.120 (1)
0.250	4.0	3.779 (–3)	7.024 (–1)	2.681	4.948	7.247	9.550	1.185 (1)	1.415 (1)	1.646 (1)	1.876 (1)	2.106 (1)
0.222	4.5	2.073 (–3)	6.253 (–1)	2.568	4.831	7.130	9.432	1.173 (1)	1.404 (1)	1.634 (1)	1.864 (1)	2.094 (1)
0.200	5.0	1.148 (–3)	5.598 (–1)	2.468	4.726	7.024	9.326	1.163 (1)	1.393 (1)	1.623 (1)	1.854 (1)	2.084 (1)
0.166	6.0	3.601 (–4)	4.544 (–1)	2.295	4.545	6.842	9.144	1.145 (1)	1.375 (1)	1.605 (1)	1.835 (1)	2.066 (1)
0.142	7.0	1.155 (–4)	3.738 (–1)	2.151	4.392	6.688	8.990	1.129 (1)	1.360 (1)	1.590 (1)	1.820 (1)	2.050 (1)
0.125	8.0	3.767 (–5)	3.106 (–1)	2.027	4.259	6.555	8.856	1.116 (1)	1.346 (1)	1.576 (1)	1.807 (1)	2.037 (1)
0.111	9.0	1.245 (–5)	2.602 (–1)	1.919	4.142	6.437	8.739	1.104 (1)	1.334 (1)	1.565 (1)	1.795 (1)	2.025 (1)

Source: Walton (1962)

Appendix B

TABLE B–1 Friction head Losses in Metres per 100 Metres Length of PVC Pipeline at Pressure Rating 4 kg/cm^2

Discharge	Pipe diameter, mm							
l/s	50	63	75	90	110	125	140	160
1.0	0.80	0.26	0.12	—	—	—	—	—
1.5	1.60	0.52	0.25	0.10	—	—	—	—
2.0	2.63	0.87	0.40	0.17	—	—	—	—
2.5	3.89	1.26	0.59	0.25	0.11	—	—	—
3.0	5.37	1.74	0.81	0.34	0.15	—	—	—
3.5	6.92	2.30	1.05	0.45	0.20	—	—	—
4.0	8.91	2.88	1.35	0.56	0.25	0.12	—	—
4.5	10.72	3.47	1.62	0.69	0.31	0.15	—	—
5.0	—	4.17	1.95	0.81	0.37	0.18	0.10	—
5.5	—	5.01	2.29	0.98	0.44	0.21	0.12	—
6.0	—	5.62	2.69	1.12	0.50	0.25	0.14	—
6.5	—	6.61	3.09	1.29	0.58	0.28	0.16	—
7.0	—	7.59	3.55	1.48	0.68	0.32	0.18	—
7.5	—	8.71	3.98	1.66	0.76	0.36	0.20	0.11
8.0	—	9.55	4.47	1.86	0.83	0.40	0.23	0.12
8.5	—	—	5.01	2.04	0.93	0.45	0.25	0.13
9.0	—	—	5.50	2.24	1.02	0.50	0.28	0.14
9.5	—	—	6.03	2.51	1.12	0.56	0.31	0.16
10	—	—	6.60	2.75	1.26	0.60	0.34	0.18
11	—	—	7.76	3.24	1.48	0.71	0.40	0.21
12	—	—	8.91	3.72	1.70	0.81	0.46	0.24
13	—	—	10.23	4.37	1.95	0.96	0.54	0.28
14	—	—	—	4.90	2.24	1.07	0.62	0.32
15	—	—	—	5.62	2.52	1.20	0.69	0.35
16	—	—	—	6.17	2.82	1.35	0.76	0.40
17	—	—	—	6.92	3.16	1.51	0.85	0.45
18	—	—	—	7.76	3.47	1.66	0.93	0.49
19	—	—	—	8.32	3.72	1.82	1.02	0.54
20	—	—	—	9.33	4.17	2.00	1.12	0.59
25	—	—	—	—	6.17	2.95	1.70	0.87
30	—	—	—	—	8.51	4.07	2.29	1.20

(*Contd.*)

TABLE B–1 Contd.

Discharge	Pipe diameter, mm							
l/s	50	63	75	90	110	125	140	160
35	—	—	—	—	11.22	5.37	2.95	1.49
40	—	—	—	—	—	6.76	3.80	2.00
45	—	—	—	—	—	8.32	4.67	2.46
50	—	—	—	—	—	10.00	5.62	2.88
60	—	—	—	—	—	—	7.59	3.98
70	—	—	—	—	—	—	10.00	5.25
80	—	—	—	—	—	—	—	6.61
90	—	—	—	—	—	—	—	8.13
100	—	—	—	—	—	—	—	10.00

TABLE B–2 Friction Head Losses in Metres per 100 Metres Length of PVC Pipeline at Pressure Rating 6 kg/cm^2

Discharge	Pipe diameter, mm							
l/s	50	63	75	90	110	125	140	160
1.0	0.89	0.29	0.13	—	—	—	—	—
1.5	1.82	0.59	0.27	0.11	—	—	—	—
2.0	3.02	0.98	0.47	0.18	—	—	—	—
2.5	4.47	1.48	0.68	0.27	0.10	—	—	—
3.0	6.17	2.04	0.91	0.37	0.14	—	—	—
3.5	8.32	2.70	1.23	0.49	0.19	0.10	—	—
4.0	10.72	3.39	1.55	0.63	0.23	0.13	—	—
4.5	—	4.17	1.86	0.76	0.28	0.15	—	—
5.0	—	4.90	2.24	0.89	0.35	0.18	—	—
5.5	—	5.89	2.69	1.10	0.41	0.22	—	—
6.0	—	6.92	3.09	1.26	0.48	0.26	0.11	—
6.5	—	7.94	3.55	1.45	0.56	0.30	0.13	0.10
7.0	—	9.12	4.17	1.70	0.63	0.34	0.14	0.11
7.5	—	10.23	4.68	1.91	0.71	0.38	0.16	0.12
8.0	—	—	5.13	2.09	0.80	0.43	0.18	0.13
8.5	—	—	5.75	2.40	0.89	0.49	0.20	0.15
9.0	—	—	6.31	2.57	0.98	0.52	0.22	0.16
9.5	—	—	7.08	2.88	1.10	0.60	0.25	0.18
10	—	—	7.76	3.16	1.20	0.65	0.27	0.20
11	—	—	9.12	3.63	1.41	0.75	0.32	0.23
12	—	—	10.72	4.37	1.66	0.89	0.37	0.27
13	—	—	—	5.01	1.91	1.05	0.44	0.32
14	—	—	—	5.62	2.19	1.15	0.49	0.35
15	—	—	—	6.46	2.46	1.32	0.55	0.40
16	—	—	—	7.24	2.75	1.48	0.62	0.47
17	—	—	—	7.94	3.09	1.66	0.69	0.50
18	—	—	—	8.91	3.39	1.82	0.76	0.55

(*Contd.*)

TABLE B–2 Contd.

Discharge l/s	Pipe diameter, mm 50	63	75	90	110	125	140	160
19	—	—	—	9.77	3.63	2.00	0.82	0.60
20	—	—	—	—	4.07	2.19	0.91	0.66
25	—	—	—	—	6.17	3.31	1.10	1.00
30	—	—	—	—	8.51	4.47	1.90	1.38
35	—	—	—	—	—	6.03	2.51	1.78
40	—	—	—	—	—	7.59	3.26	2.29
45	—	—	—	—	—	9.33	3.98	2.82
50	—	—	—	—	—	—	4.79	3.39
60	—	—	—	—	—	—	6.46	4.88
70	—	—	—	—	—	—	8.32	6.17
80	—	—	—	—	—	—	10.72	7.76
90	—	—	—	—	—	—	—	9.55

TABLE B–3 Friction Head Losses in Metres per 100 Metres Length of PVC Pipeline at Pressure Rating 10 kg/cm^2

Discharge l/s	Pipe diameter, mm 20	25	32	40	50	63	75	90	100	125
0.1	1.62	0.54	0.17	—	—	—	—	—	—	—
0.2	5.37	1.78	0.55	0.20	—	—	—	—	—	—
0.3	14.00	3.55	1.12	0.40	0.14	—	—	—	—	—
0.4	—	5.90	1.82	0.65	0.22	—	—	—	—	—
0.5	—	8.71	2.75	0.96	0.32	0.11	—	—	—	—
0.6	—	12.02	3.72	1.32	0.45	0.15	—	—	—	—
0.7	—	—	5.01	1.74	0.59	0.20	—	—	—	—
0.8	—	—	6.03	2.19	0.72	0.24	0.10	—	—	—
0.9	—	—	7.59	2.69	0.91	0.30	0.13	—	—	—
1.0	—	—	9.12	3.16	1.10	0.36	0.16	—	—	—
1.2	—	—	12.60	4.47	1.51	0.50	0.21	—	—	—
1.4	—	—	—	5.90	2.00	0.66	0.28	0.12	—	—
1.6	—	—	—	7.24	2.51	0.81	0.35	0.15	—	—
1.8	—	—	—	8.91	3.02	1.00	0.44	0.18	—	—
2.0	—	—	—	10.96	3.63	1.23	0.52	0.22	—	—
2.5	—	—	—	—	5.37	1.78	0.78	0.33	0.13	—
3.0	—	—	—	—	7.41	2.46	1.10	0.45	0.18	—
3.5	—	—	—	—	9.77	3.24	1.41	0.59	0.24	0.13
4.0	—	—	—	—	12.30	4.07	1.78	0.74	0.30	0.16
4.5	—	—	—	—	—	5.01	2.19	0.91	0.37	0.20
5.0	—	—	—	—	—	6.03	2.57	1.10	0.45	0.23
6.0	—	—	—	—	—	8.32	3.55	1.51	0.60	0.32

(*Contd.*)

TABLE B–3 Contd.

Discharge	Pipe diameter, mm									
l/s	20	25	32	40	50	63	75	90	100	125
7.0	—	—	—	—	—	10.72	4.68	2.00	0.79	0.44
8.0	—	—	—	—	—	—	5.75	2.46	1.00	0.54
9.0	—	—	—	—	—	—	7.08	3.09	1.23	0.68
10	—	—	—	—	—	—	8.71	3.72	1.48	0.79
12	—	—	—	—	—	—	12.00	5.01	2.00	1.82
14	—	—	—	—	—	—	—	6.61	2.69	1.48
16	—	—	—	—	—	—	—	8.13	3.31	1.86
18	—	—	—	—	—	—	—	10.00	4.07	2.24
20	—	—	—	—	—	—	—	—	5.01	2.82

Source: Kirloskar Brother's Engineering data

Appendix C

(BIS) Bureau of Indian Standards Codes for Rotodynamic Pumps/Pumping System

S. No.	BIS Code	Description
Pumps		
1.	IS 1710 : 1989	Specification for pumps - vertical turbine mixed and axial flow, for clear cold water
2.	IS 6595 : Part 1: 2002	Horizontal centrifugal pumps for clear, cold water - specification - Part 1 : agricultural and rural water supply purposes
3.	IS 6595 : Part 2: 1993	Horizontal centrifugal pumps for clear, cold water - Part 2: general purposes other than agricultural and rural water supply - specification
4.	IS 7538 : 1996	Three-phase squirrel cage induction motors for centrifugal pumps for agricultural applications
5.	IS 8034 : 2002	Submersible pump sets - specification
6.	IS 8035 : 1999	Hand pump - shallow well - specification
7.	IS 8418 : 1999	Pumps – centrifugal self priming – specification (first revision)
8.	IS 8472 : 1998	Pumps – regenerative for clear, cold water – specification (first revision)
9.	IS 9079 : 2002	Electric monoset pumps for clear, cold water for agricultural and water supply purposes - specification
10.	IS 9137 : 1978	Code for acceptance test for centrifugal, mixed flow and axial pumps - class c
11.	IS 9283 : 1995	Motors for submersible pump sets - specification
12.	IS 9464 : 1980	Specification for horizontal centrifugal pumps for marine use
13.	IS 9542 : 1980	Specification for horizontal centrifugal monoset pumps for clear, cold, fresh water
14.	IS 9694 : Part 1: 1987	Code of practice for the selection, installation, operation and maintenance of horizontal centrifugal pumps for agricultural applications - Part 1 : selection
15.	IS 9694 : Part 2 : 1980	Code of practice for the selection, installation, operation and maintenance of horizontal centrifugal pumps for agricultural application - Part 2: installation
16.	IS 9694 : Part 3 : 1980	Code of practice for the selection, installation, operation and maintenance of horizontal centrifugal pumps for agricultural applications - Part 3: operation
17.	IS 9694 : Part 4 : 1980	Code of practice for the selection, installation, operation and maintenance of horizontal centrifugal pumps for agricultural applications - Part 4 : maintenance
18.	IS 10572 : 1983	Method of sampling pumps
19.	IS 10981 : 1983	Class of acceptance test for centrifugal mixed flow and axial pumps - Class B
20.	IS 11501 : 1986	Specification for engine monoset pumps for clear, cold, fresh water for agricultural purposes

(*Contd.*)

S. No.	BIS Code	Description
Pumps		
21.	IS 11346 : 2002	Tests for agricultural and water supply pumps – code of acceptance (first revision)
22.	IS 11745 : 1986	Technical supply conditions for positive displacement pumps – reciprocating
23.	IS 12225 : 1997	Centrifugal jet pump – specification
24.	IS 12732 : 1989	Deep well hand pump – nomenclature, identification and packaging of components
25.	IS 13139 : 1992	End suction centrifugal pumps – base plate and installation – dimensions
26.	IS 13518 : 1992	End suction centrifugal pumps (rating 16 bar) – designation, nominal duty point and dimensions
27.	IS 13537 : 1993	Technical specification for centrifugal pumps – class 2
28.	IS 14106 : 1996	Direct action hand pumps – specification
29.	IS 14220 : 1994	Open well submersible pump sets – specification
30.	IS 14536 : 1998	Selection, installation, operation and maintenance of submersible pump set – code of practice
31.	IS 14582 : 1998	Single-phase small A.C. electric motors for centrifugal pumps for agricultural applications
32.	IS 15500 : Parts 1 to 8 : 2004	Deep well hand pumps, components and special tools – specification
Tube Wells		
1.	IS 2800 : Part 1 : 1991	Code of practice for construction and testing of tube wells/bore wells– Part 1: construction
2.	IS 2800 : Part 2 : 1979	Code of practice for construction and testing of tube wells/bore wells – Part 2 testing
3.	IS 4097 : 1967	Specification for gravel for use as pack in tube wells
4.	IS 8110 : 2000	Well screens and slotted pipes – specification
5.	IS 11189 : 1985	Methods for tube well development
6.	IS 11632 : 1986	Code of practice of rehabilitation of tube well
7.	IS 460 : Part 2 : 1985	Specification for test sieves – Part 2: perforated plate test sieve (third revision)
8.	Is 460 : Part 3 : 1985	Specification for test sieve – Part 3 : Methods of examination of apertures of test sieves (third revision)
Hydraulic Rams		
1.	IS 10808 : 1984	Code of practice for installation, operation and maintenance of hydraulic rams
2.	IS 10809 : 1984	Specification for hydraulic rams
3.	IS 11390 : 1985	Test code for hydraulic rams
Ground Water		
1.	IS 4410 : Part 11 : Sec 6 : 1994	Glossary of terms relating to river valley projects – Part 11 : hydrology – section 6 : ground water
Drilling Rigs		
1.	IS 7156 : 1974	General requirements for reverse circulation drilling rigs
2.	IS 7206 : Part 1 : 1986	General requirements for direct circulation rotary drilling rigs – Part 1: with rotary table
3.	IS 7209 : 1974	General requirements for blast hole drilling rigs
4.	IS 9439 : 2002	Glossary of terms used in water-well drilling technology
5.	IS 10208 : 1982	Specification for diamond core drilling equipment

(*Contd.*)

Drilling Rigs		
6.	IS 11180 : Part 1 : 1985	Specification for kellys for direct rotary drilling – Part 1 : square and hexagonal kellys
7.	IS 12097 : 1994	Classification and selection of drilling rigs for water well drilling
8.	IS 12682 : 1989	Water well drilling – percussion drilling rigs – general requirements
Pipes and Fittings		
1.	IS 12231 : 1987	Specification for unplasticized PVC pipes for use in suction and delivery lines of agricultural pump sets
2.	IS 13593 : 1992	Specification for UPVC pipe fittings to be used with the UPVC pipes in the suction and delivery lines of agricultural pumps
3.	IS 15265 : 2003	Flexible PVC pipes or polymer reinforced thermoplastic hoses for suction and delivery lines of agricultural pumps – specification
4.	SP 57 (QAWSM) : 1993	Handbook on pipes and fittings for drinking water supply
5.	IS 10804 : 1994	Recommended pumping system for agricultural purposes
6.	IS 10805 : 1986	Foot valves, reflux valves or non-return valves and bore valves to be used in suction lines of agricultural pumping systems
7.	IS 14263 : 1995	Tapers for agricultural pumping systems – specification
8.	IS 8360 : Part 1 : 1977	Specification for fabricated high density polyethylene (HDPE) fittings for potable water supplies: Part 1 General requirements
9.	IS 8360 : Part 2 : 1977	Specification for fabricated high density polyethylene (MDPE) fittings for potable water supplies: Part 2 Specific requirements for 90 tees
10.	IS 8360 : Part 3 : 1977	Specification for fabricated high density polyethylene (HDPE) fittings for potable water supplies: Part 3 specific requirements for 90 bends
11.	IS 10124 : Part 1 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 1 general requirements
12.	IS 10124 : Part 2 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 2 specific requirements for sockets
13.	IS 10124 : Part 3 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 3 specific requirements for straight reducers
14.	IS 10124 : Part 4 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 4 specific requirements for caps
15.	IS 10124 : Part 5 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 5 specific requirements for equal tees
16.	IS 10124 : Part 6 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 6 specific requirements for flanged tail piece with metallic flanges
17.	IS 10124 : Part 7 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 7 specific requirements for threaded adaptors
18.	IS 10124 : Part 8 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 8 specific requirements for 90 degree bends
19.	IS 10124 : Part 9 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 9 specific requirements for 60 degree bends
20.	IS 10124 : Part 10 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 10 specific requirements for 45 degree bends
21.	IS 10124 : Part 11 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 11 specific requirements for 30 degree bends

(*Contd.*)

Pipes and Fittings		
22.	IS 10124 : Part 12 : 1988	Specification for fabricated PVC fittings for potable water supplies: Part 12 specific requirements for 22 $\frac{1}{2}$ degree bends
23.	IS 10124 : Part 13 : 1988	specification for fabricated PVC fittings for potable water supplies: Part 13 specific requirements for 11 $\frac{1}{4}$ degree bends
24.	IS 7834 : Part 1 : 1987	Specification for injection moulded PVC fittings with solvent cement joints for water supplies: Part 1 general requirements
25.	IS 7834 : Part 2 : 1987	Specification for injection moulded PVC fittings with solvent cement joints for water supplies: Part 2 specific requirements for 45 degrees elbows
26.	IS 7834 : Part 3 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 3 specific requirements for 90 degree elbows
27.	IS 7834 : Part 4 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 4 specific requirements for 90 degree tees
28.	IS 7834 : Part 5 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 5 specific requirements for 45 degree tees
29.	IS 7834 : Part 6 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 6 specific requirements for sockets
30.	IS 7834 : Part 7 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 7 specific requirements for unions
31.	IS 7834 : Part 8 : 1987	Specification for injection moulded PVC socket fittings with solvent cement joints for water supplies: Part 8 specific requirements for caps
32.	IS 7181 : 1986	Horizontally cast iron double flanged pipes for water, gas and sewage
33.	IS 8008 : Part 1 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 1 : general requirements for fittings
34.	IS 8008 : Part 2 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 2 : specific requirements for 90° bends
35.	IS 8008 : Part 3 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 3 : specific requirements for 90° tee
36.	IS 8008 : Part 4 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 4 : specific requirements for reducers
37.	IS 8008 : Part 5 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 5 : specific requirements for ferrule reducers
38.	IS 8008 : Part 6 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 6 : specific requirements for pipe ends
39.	IS 8008 : Part 7 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification – Part 7 : specific requirements for sandwich flanges
40.	IS 8008 : Part 8 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification : Part 8 specific requirements for reducing tees
41.	IS 8008 : Part 9 : 2003	Injection moulded/machined high density polyethylene (HDPE) fittings for potable water supplies – specification : Part 9 specific requirements for ends caps

(*Contd.*)

Belt and Pulleys		
1.	IS 1691 : 1980	Specification for cast iron and mild steel flat pulleys
2.	IS 2122 : Part I : 1973	Code of practice for selection, storage, installation and maintenance of belting for power transmission: Part I Flat belt drives
3.	IS 2122 : Part 2 : 1991	Power transmission – Belts – Code of practice for selection, storage, installation and maintenance of belting for power transmission: Part 2 V-belt drive
4.	IS 2494 : Part 1 : 1994	V-belts – endless V-belts for industrial purposes – Part 1 : general purpose – specification
5.	IS 2693 : 1989	Power transmission – bush type flexible coupling
6.	IS 3142 : 1993	Pulleys-V-grooved pulleys for endless V-belts sections Z, A, B, C, D and E and endless wedge belts sections SPZ, SPA, SPB and SPC - specification
7.	IS 5593 : 1980	Specification for belt fasteners (alligator type)
8.	IS 5635 : 1983	Specification for automotive V-belt drives
9.	IS 7923 : 1985	Glossary of terms and definitions relating to drives using V-belts and grooved pulleys
10.	IS 10288 : 1982	Specification for belt-fasteners, plate type

Source: BIS e-Catalogue, www.bis.org.in

Appendix D

Conversion Factors

Length

1 metre	= 3.2808 feet
1 metre	= 39.37 inches
1 centimetre	= 0.3937 inch
1 kilometre	= 0.6214 mile
1 foot	= 0.3048 metre
1 inch	= 2.54 centimetres
1 mile	= 5,280 feet
1 mile	= 1.609 kilometres

Area

1 square metre	= 10.764 square feet
1 square centimetre	= 0.155 square inch
1 square kilometre	= 100 hectares
1 square kilometre	= 0.3861 square mile
1 hectare	= 10,000 square metres
1 hectare	= 107,640 square feet
1 hectare	= 2.471 acres
1 square foot	= 0.0929 square metre
1 square inch	= 6.452 square centimetres
1 acre	= 43,560 square feet
1 acre	= 0.4047 hectare
1 square mile	= 640 acres
1 square mile	= 258.99 hectares
1 square mile	= 2.59 square kilometres

Volume

1 cubic metre	= 35.314 cubic feet
1 cubic metre	= 1.308 cubic yards
1 cubic metre	= 1,000 litres
1 litre	= 0.0353 cubic foot
1 litre	= 0.2642 U.S. gallon
1 litre	= 0.2201 Imperial gallon
1 cubic centimetre	= 0.061 cubic inch

1 cubic foot	= 0.0283 cubic metre
1 cubic foot	= 23.32 litres
1 cubic foot	= 7.40 U.S. gallons
1 cubic foot	= 6.23 Imperial gallons
1 cubic inch	= 16.39 cubic centimetres
1 cubic yard	= 0.7645 cubic metre
1 U.S. gallon	= 3.7854 litres
1 U.S. gallon	= 0.833 Imperial gallon
1 Imperial gallon	= 1.201 U.S. gallon
1 Imperial gallon	= 4.5436 litres
1 acre-foot	= 43,560 cubic feet
1 acre-foot	= 1,233.5 cubic metres
1 acre-inch	= 3,630 cubic feet
1 arce-inch	= 102.8 cubic metres

Rates of Flow

1 cubic metre per second	= 35.314 cubic feet per second
1 cubic metre per hour	= 0.278 litres per second
1 cubic metre per hour	= 4.403 U.S. gallons per minute
1 cubic metre per hour	= 3.668 Imperial gallons per minute
1 litre per second	= 0.0353 cubic foot per second
1 litre per second	= 15.852 U.S. gallons per minute
1 litre per second	= 13.206 Imperial gallons per minute
1 litre per second	= 3.6 cubic metres per hour
1 cubic foot per second (second-foot or cusec)	= 0.0283 cubic metres per second
1 cubic foot per second	= 28.32 litre per second
1 cubic foot per second	= 448.8 U.S. gallons per minute
1 cubic foot per second	= 1 acre inch per hour (approx.)
1 cubic foot per second	= 373.8 Imperial gallons per minute
1 cubic foot per second	= 2 acre foot per day (approx.)
1 U.S. gallon per minute	= 0.06309 litres per second
1 Imperial gallon per minute	= 0.07573 litre per second

Useful Approximations

5 centimetre	= 2 inches
10 centimetre	= 4 inches
30 centimetre	= 1 foot
10 metres	= 33 feet
10 kilometre	= 6 miles
16 kilometre	= 10 miles
1 hectare	= 2.5 acres
1 square inch	= 6.5 square centimetres
1 square metre	= 11 square feet
16.4 cubic centimetres	= 1 cubic inch
35 cubic feet	= 1 cubic metre

English (EPS)/Metric Conversion Constants

Measure	FPS		Metric	
	Unit	**FPS to Metric**	**Unit**	**Metric to FPS**
Length	inch (″)	× 25.4	mm = $\frac{1}{1000}$ m	× 0.03937
	foot(′) = 12″	× 0.3048	m	× 3.28
	yard = 3′	× 0.9144	m	× 1.09361
	mile = 1,760 yd.	× 1.6093	km = 1,000 m	× 0.621
	nautical mile	× 1.852	km = 1,000 m	× 2.540
Area	square inch	× 6.451	cm^2	× 0.1550
	square foot	× 0.0929	m^2	× 10.764
	acres	× 0.4047	hectare	× 2.471
Volume	cubic inch	× 16.3871	cm^3	× 0.0610
	Imperial gallon (= 1.2 American gallon)	× 4.546	litre = (dm^3)	× 0.220
	Imperial gallon (= 10 lb)	× 0.004546	m^3	× 2.20
	American gallon	× 3.785	litre	× 0.2642
	Petroleum barrel = 42 American gallons	× 1.59	hl	x 0.63
	cubic foot	× 28.316	litre	× 0.0353
	cubic foot	× 0.0283	m^3	× 35.38
Weight	grain = $\frac{1}{7000}$	× 0.0648	gr	× 0.035
	ounce = $\frac{1}{16}$ lb	× 28.35	gr	× 15.42
	pound = 1 lb	× 0.4536	g	× 2.205
	cwt = 112 lb	× 50.802	kg	× 0.0197
	short ton or American ton = 2,000 lb	× 0.907	tonne	× 1.102
	long ton = 2,243 lb	× 1.016	tonne	× 0.98421
Pressure	Pound/square inch $= \frac{\text{foot of water}}{2.31}$	× 0.0703	$kg/cm^2 = \frac{\text{m of water}}{10}$	× 14.22
	pound/square inch	× 0.068	atm	× 14.7
	long ton/square inch	× 157.5	kg/cm^2	× 0.00635
	inch mercury	× 345	mm of water	× 0.0029
	$= \frac{\text{foot of water}}{1.13}$ inch mercury	× 25.4	mm of mercury	× 0.03937
	1 atm (34 feet of water or = 14.7 pound/square inch)	× 1.033	1 atm. (10 m of water or 1 kg/cm^2)	× 0.967

(*Contd.*)

Measure	FPS		Metric	
	Unit	FPS to Metric	Unit	Metric to FPS
Density	pound/cubic foot	× 16.02	kg/m^3	× 0.0625
	pound/cubic foot	× 0.01602	kg/dm^3 or kg/litre	× 62.424
	pound/cubic inch	× 27.6799	kg/cm^3	× 0.0362
Velocity	foot/second	× 0.3048	m/sec	× 3.28
	foot/minute	× 0.00508	m/sec	× 196.85
Rate of discharge	cubic foot/second (cusec)	× 0.0283	m^3/sec	× 35.38
	cubic foot/second (cusec)	× 28.316	lit/sec (= dm^3/sec)	× 0.0353
	cubic foot/minute	× 0.472	lit/sec (= dm^3/sec)	× 2.22
	gallon/minute (gpm)	× 0.0757	lit sec (= dm^3/sec)	× 13.22
	gallon/minute (gpm)	$\times \frac{0.0757}{1000}$	m^3/sec	$\times 13.22 \times 10^3$

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Authors' Profiles

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