10 Groundwater withdrawal

Revised and updated by
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10.1 Introduction

For community water supply systems, groundwater is almost always the preferred source. Surface water sources are very likely to be contaminated and much more subject to seasonal fluctuation. Groundwater withdrawals often can be continued long after drought conditions have depleted the rivers and streams. Use of groundwater for community water supplies is probably still very much below its potential in many countries.

Frequently, available data on groundwater resources are grossly inadequate. Successful development of groundwater supplies may then be promoted by prospecting (exploration) studies. These bring to light the physical and chemical characteristics of the groundwater as well as the potential yield.

Tapping of groundwater resources, both for drinking water supply and for irrigation purposes, dates back to ancient times. In China at least 3000 years ago, wells were being drilled with hand-operated churn drills to depths as great as 100 m and lined with bamboo casings. Hand-dug wells have been sunk since time immemorial, sometimes to a considerable depth, and such wells continue to be constructed in several parts of the world. The technology for tapping groundwater at great depth through boreholes/tubewells[1] is more recent.

The first type of water well drilling that came into general use was the cable-tool (percussion) method. Over a period of several centuries it has developed from crude forms to a number of fairly sophisticated techniques. The need to prevent the collapse of un-stable ground formations and the problems of controlling at depth the heavy tools required for percussion drilling, encouraged the development of other drilling methods. These use rotating cutters or *bits* that bore into the ground while a fluid is passed through them (direct-circulation rotary drilling). For water supply wells, use of a clay-based mud fluid causes problems, as the aquifers to be tapped tend to clog up. This led to development of the reverse-circulation rotary drilling method in which a high-rate flow of clean water is used to carry the cuttings out of the drilled hole. A later logical step was the pneumatic tool placed at the bottom of the drill pipe. In the 1950s, the d*own-the-hole hammer* drilling method was introduced. The efficiency of this tool proved remarkable and, even in hard-rock formations, small-diameter holes may now be drilled in a fraction of the time previously required.

1 The words *borehole* and *tubewell* are used interchangeably in different parts of the world. In this publication, *borehole* will be used from now on.

No particular water well drilling technique is applicable under all conditions. Any well construction method can be suitable, depending on the circumstances, though the general trend is towards rotary drilling to reduce time and cost. So, techniques for reaching the groundwater range from ancient methods such as the simple digging of wells with hand tools, and the excavation of the famous ganats (underground galleries extending many kilometres) in Iran and Afghanistan, to the sophisticated drilling machines (*drilling rigs*) capable of making a borehole some hundreds of metres deep even in hard-rock formations.

10.2 Groundwater occurrence and prospecting

Prospecting for water requires a basic knowledge of the various kinds of groundwater-bearing formations that can be found in the earth's crust.

Occurrence

Groundwater occurs in pores, voids or fissures of ground formations. Pores are the spaces between the mineral grains in sedimentary ground layers and in decomposed rocks. The amount of pore space in a ground formation depends upon such factors as grain size, shape, packing and the presence of cementing material. Porosity is the ratio of pore space to total ground volume (Fig. 10.1). A high porosity does not always indicate good permeability (water-bearing potential). Although clays and silts have a high porosity, the size of the pores is too small to allow water to flow easily.

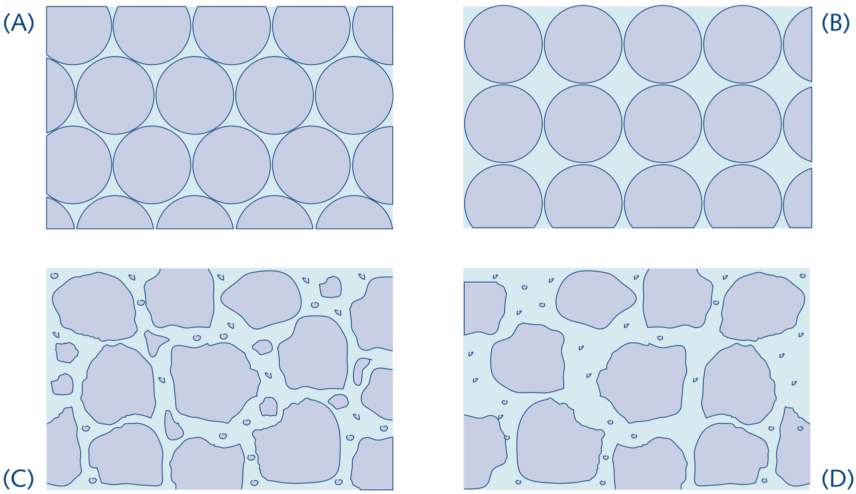
All openings in rocks such as joints, bedding, cleavage planes and random cracks are called fissures in hydrogeological terminology. Igneous[2] rocks are not generally porous unless they have been decomposed by weathering. Lavas, which contain cavities formed by gas bubbles that escaped during the eruption, can be an exception. Even when a ground formation is highly porous the permeability may be very low because the voids are not always inter-connected. Fissures may also occur in sedimentary[3] rocks.

Geologically young and unweathered fissures in all types of ground formation tend to be closed and are likely to contain little or no water. As weathering proceeds, the fissures will open up near the ground surface but remain closed at depth.

Aquifers (water-bearing ground formations) that hold most of their water in large joints and fissures are called pervious, whereas those with the water in pores are called porous. Table 10.1 shows common ground types and the way water usually occurs in them.

2 Igneous: originating by solidification of molten or partly molten material (magma)

3 Sedimentary: resulting from the consolidation of layers of loose fragmental material by pressure to form rock



(A) Close packing of spheres: porosity is 26%
(B) Open packing of spheres: porosity is 4%
(C) Poorly graded sand, porosity reduced by presence of small grains
(D) Well-graded sand (i.e. grains mainly of one size), porosity reduced by cemented deposits (stippled) between the grains

Fig. 10.1. Porosity and texture

Table 10.1 Usual mode of water occurrence

Ground type	Water usually occurring in:
Sand and gravel	Pores
Sandstone	Pores and fissures
Limestone	Fissures often expanding into caves
Chalk	Pores and fissures
Clay	Very small pores
Massive igneous	Fissures with pores in weathered zones
Lava	Fissures with pores in igneous zones
Metamorphic	Fissures with pores in weathered zones

The ease with which water can flow through a ground formation under a hydraulic head is termed the hydraulic permeability coefficient. Hydraulic permeability coefficient is ex-pressed as the velocity of flow of water through the ground per unit of hydraulic gradient, e.g. mm/s or m/d. It depends on the porosity, the average pore size and the distribution of the fissures (see table 10.2).

Ground layers with a very low hydraulic permeability (less than about 10-6 mm/sec) are said to be impermeable and those with higher hydraulic permeability are regarded as permeable.

Table 10.2 Porosity and hydraulic permeability for some common ground materials

Material	Porosity (%)	Hydraulic permeability coefficient in mm/s
Clay	45-55	10^{-3} - 10^{-9}
Silt	40-50	10^{-2} - 10^{-6}
Sand	35-40	10^{-1} - 10^{-2}
Clean gravel	40-45	10^{3} – 10^{1}
Sandy gravel	25-40	10^{1} – 10^{-2}
Sandstone	10-20 (pores) (fissures)	10^{-4} - 10^{-6} 10^{-1}
Limestone	1-10 (pores) (fissures)	10^{-6} - 10^{-8} 10^{2}
Granite (fresh)	1 (pores) (fissures)	10^{-10} 10^{2}

Figure 10.2 shows the distribution of water in and above an unconfined aquifer.

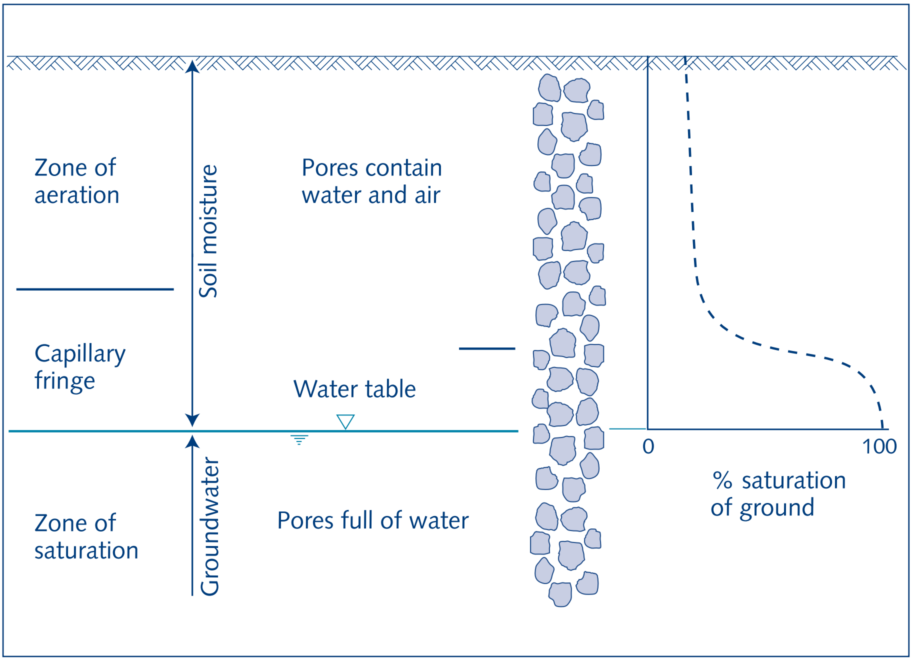


Fig. 10.2. Water distribution above and in a porous unconfined aquifer

An unconfined aquifer is open to infiltration of water directly from the ground surface. This is illustrated in figures 10.3a and 10.3b.

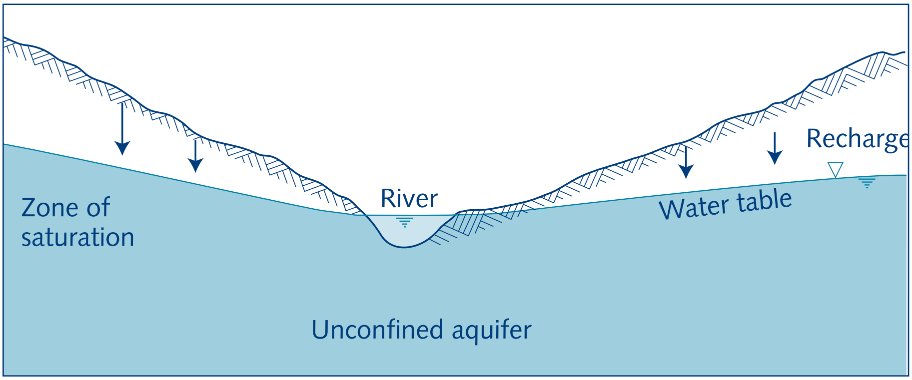


Fig. 10.3a. Infiltration of water into an unconfined aquifer during the wet season

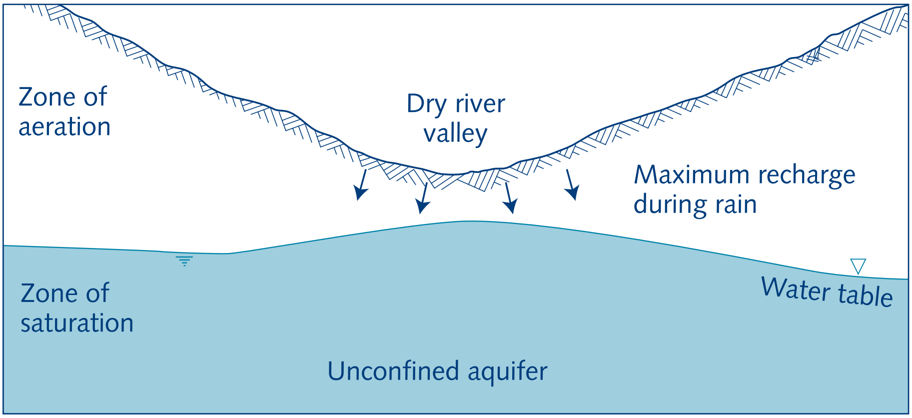


Fig. 10.3b. Infiltration of water into an unconfined aquifer during the dry season

A confined aquifer (Fig. 10.4) is one where the water-bearing ground formation is capped by an impermeable ground layer. The water pressure in a confined aquifer is related to the water level in its recharge area.

The water pressure in a confined aquifer can be measured by drilling into it and observing the level to which the water rises in the borehole. This water level is called the piezometric level. If the piezometric level is above the ground surface, water from the aquifer will naturally overflow from the borehole, which is then called a free-flowing artesian well.

Infiltration of water from the ground surface through permeable ground towards the groundwater table will be halted where a lens of impervious ma-terial such as clay is present (fig.10.5). Water will then accumulate in the ground above this lens, forming a perched water table of some distance above the real groundwater table. It is very

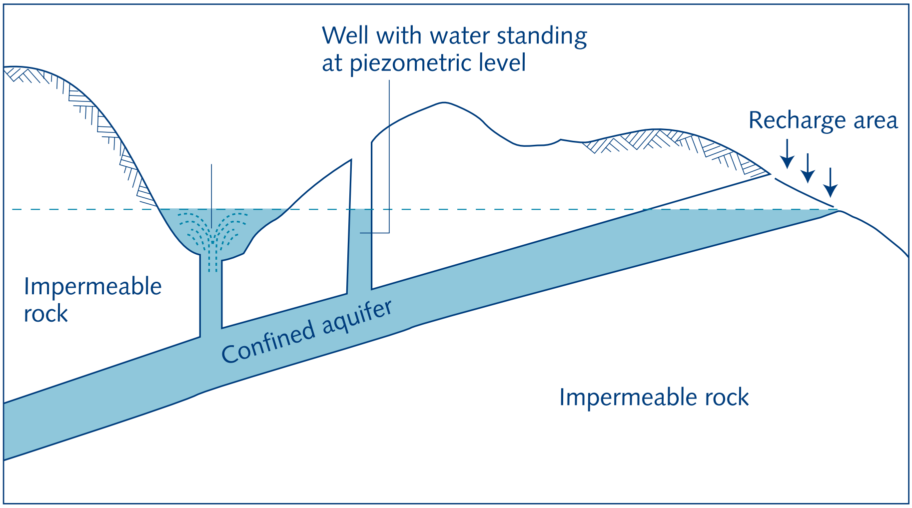


Fig. 10.4. Confined aquifer fed from a recharge area

important to identify a perched water table since the amount of water it contains is often small. Frequently, perched water tables will disappear during dry periods when there is no recharge by infiltration from the ground surface.

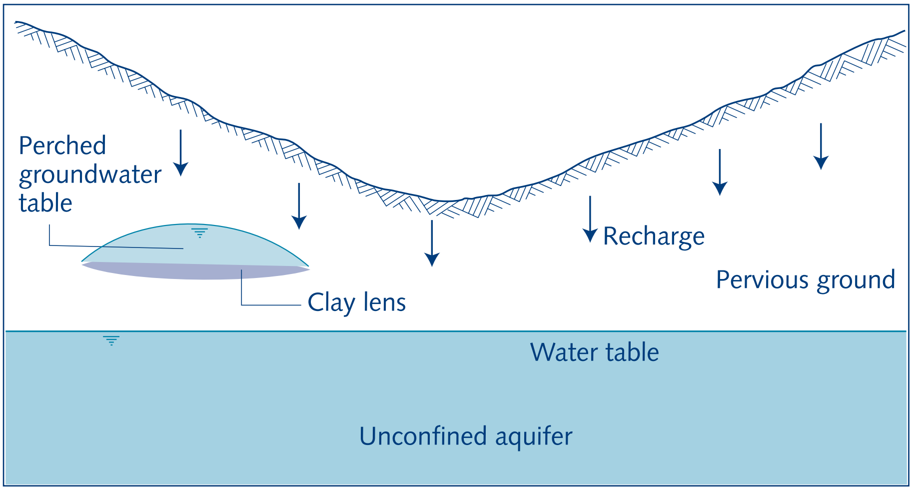


Fig. 10.5. Perched water table

Prospecting

Successful prospecting for groundwater requires knowledge of the manner in which water exists in the water-bearing ground formations. Without this knowledge, effective and efficient water exploration is impossible, and well drilling then becomes rather like a game of roulette. The aim of the prospecting work must be clearly defined. Is it for providing a small local supply or is it to determine aquifer characteristics for the development of the ground-water resources of an entire area?

Available hydrogeological information about the study area should be collected and collated. This may include: geological maps and reports, topographical maps, logs of boreholes, surface geological reconnaissance, meteorological records, and hydrological data.

A survey of the study area should be made, preferably towards the end of the dry season. This survey also taps the indigenous knowledge of local men and women on the history of water sources, water quality and land uses. They also know the flood-prone areas not suitable for well development. Consultation with both sexes is needed because in most cultures men and women have different tasks. Hence their knowledge of water resources also differs. In cultures where male outsiders cannot talk with women, it is often possible to sound out women on their knowledge and needs through a local intermediary such as a female teacher or health worker. In some cases a survey may be all that is needed for an experienced hydrogeologist to define water sources for small community supplies and no further investigation will then be required. If essential data are lacking, some fieldwork is necessary.

The survey should provide sufficient data to form a basis for drawing up a hydrogeological map showing: the distribution of aquifers; any springs or signs of springs present; depth of water tables and piezometric levels; yield of existing groundwater sources; and the quality of the water from them. Sometimes, it is possible to prepare such a map on the basis of an examination of outcrops and existing water supplies. In other cases, it may involve the use of specially drilled boreholes and geophysics. Drilling special test boreholes will usually only be required when an aquifer is to be fully exploited and knowledge is therefore needed of the hydraulic permeability and water storage capacity.

Geophysical investigations, especially electrical resistivity measurements, are very useful in understanding the distribution and quality of groundwater. The value of the electrical resistance of a ground formation depends upon the amount, distribution and conductivity of the water it contains. Resistivity measurements are made by passing an electric current through the ground between two electrodes and measuring the voltage drop between two further electrodes (Fig. 10.6). The depth of penetration of the current is controlled by the spacing of the electrodes. Increasing the electrode spacing makes the current penetrate deeper, and so a complete resistivity depth probe can be carried out. If a depth probe is done near an existing well or borehole of which the water level, water quality and aquifer thickness are known, then the correlation between the resistivity values and the hydrogeological conditions can be established. This provides a basis for interpreting resistivity depth probes in other areas with much the same geology, to establish information on water table depth, water quality and aquifer thickness.

If resistivity measurements are conducted in a grid pattern over an area, the readings can be plotted on a grid map to form patterns of high and low resistivity for each electrode spacing

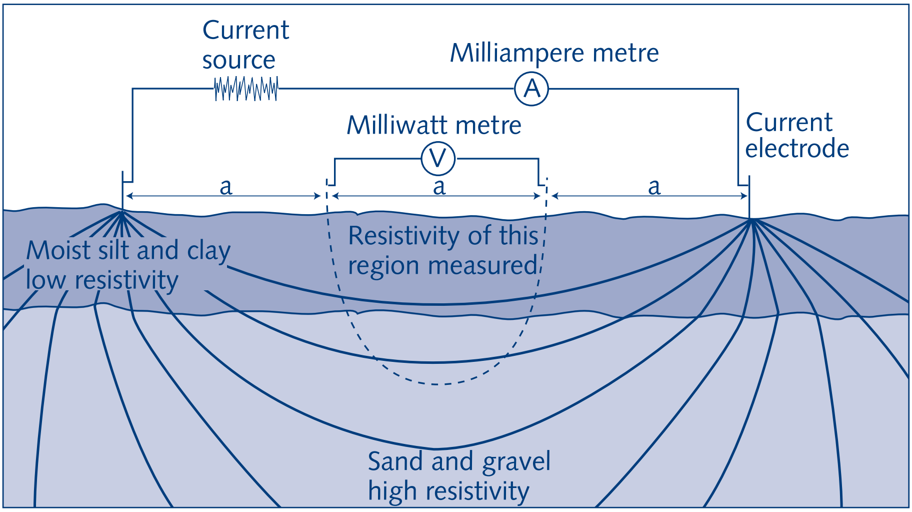


Fig. 10.6. Electrical resistivity measuring arrangement

used. Lines of equal resistivity can then be drawn on the map to highlight areas of low resistivity. These are more likely than high-resistivity areas to be permeable and water-bearing ground formations.

Sometimes it is necessary to drill small boreholes for pros-pecting purposes to supplement the data obtained from surface geophysical methods. This method is always expensive and often difficult to employ. To obtain the maximum amount of information from a borehole, geophysical logging may be necessary. This involves lowering measuring instruments down the borehole to record ground and water properties. Borehole logging is a complex operation and advice should always be obtained from a geophysicist before it is decided upon. Other, more sophisticated, geophysical techniques for groundwater prospecting are seismic and gravity measurements.

Annex 2 gives a detailed description of the most common methods used in groundwater exploration. Included are:

- Study of any available geological maps and reports
- Study of topographical maps (e.g. 1: 50,000 scale)
- Examination of any existing wells
- Hydrogeological survey
- Surface geophysical investigations (including electrical resistivity, seismic refraction, well logging)
- Aerial photography and satellite imagery
- Airborne geophysical methods (including magnetic, radiometric and electro-magnetic measurements)
- Test wells (drilling, pumping tests, geophysical logging, radioactivity logging, (radio isotopic) tracer investigations, chemical water testing (electric conductivity))

Safe yield

The safe yield of an aquifer is the maximum withdrawal rate that can be permanently obtained without depleting the source. Safe yield is estimated to check whether the planned withdrawal for water supply purposes will be safeguarded in the long run. Basically, the amount of water withdrawn should not exceed the natural recharge. Another limitation is that the groundwater table should not be lowered so much that polluted water from elsewhere would be drawn into the aquifer. Sometimes withdrawal of water from a new well may cause an appreciable reduction of the yield of existing wells nearby. In an area where little is known about the extent and capacity of the aquifer, the new well and any nearby wells should be monitored at least during the early period of operation. Public access to information on the maximum safe yield of wells helps reduce risks of overexploitation by the elite. Without conscious information sharing, the elite often have a monopoly over newly emerging data and may use them for personal interests. In addition, local water management organisations can be encouraged to set rules and control water extraction (see also chapter 5: Integrated Water Resources Management).

10.3 Methods of groundwater withdrawal

The oldest and simplest method of groundwater withdrawal is to dig a hole in the ground to a depth below the groundwater table. Usually the amount of water that can be collected in this manual way is quite limited. When more withdrawal capacity is needed, the aquifer must be tapped over a greater area of contact. This may be done by enlarging the width of the excavation (horizontal), by extending it to greater depth (vertical), or by increasing both the width and depth. Which of these methods can and should be applied in a particular case depends on the thickness of the water-bearing ground formation, the depth of the groundwater table and, in case of community inputs, the balance between the inputs and benefits of each method.

Horizontal means

The horizontal means of groundwater withdrawal are called galleries and may be subdivided into seepage ditches, infiltration drains (Fig 10.7) and tunnels (Fig. 10.8).

Because of the difficulties and costs of excavation, galleries should only be used in cases where the groundwater table is at a shallow depth – not more than 5-8 m below the ground surface. In consolidated ground formation, tunnels may still be economical at greater depths. Galleries offer the only practical solution when groundwater is to be withdrawn from shallow aquifers with a small saturated thickness, as these aquifers have to be tapped over a large contact area. Galleries are also recommended in coastal areas where the fresh water to be withdrawn floats on top of underlying salt water.

Drawdown[4] of the fresh water table must then be kept as small as possible, otherwise the salt water would rise and mix with the fresh water.

Ditches are easy to construct; they can have a large capacity and a long useful life. However, ditches being open, the water collected in them is unprotected against contamination, which makes them less suited for drinking water supply purposes.

Infiltration drains and **tunnel**s are more costly to build, and their design is more complicated. Drains may be subject to clogging. The advantage of drains and tunnels is that these collectors are completely underground, so the collected water is protected against any contamination from the ground surface.

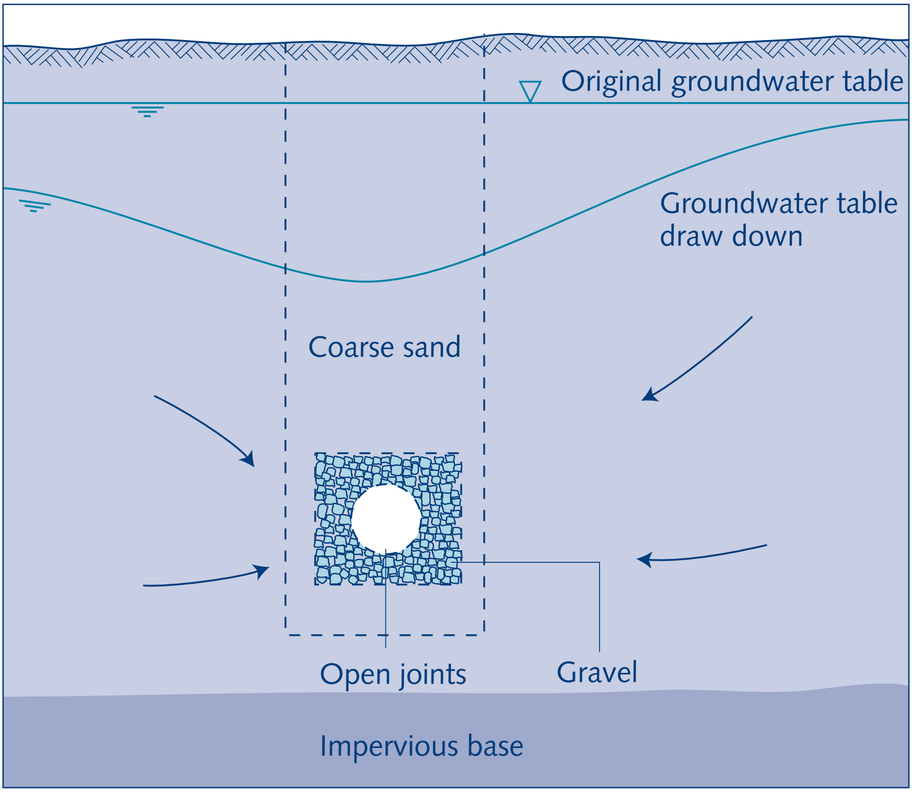


Fig. 10.7. Infiltration drain

4 Drawdown is the lowering of the groundwater table around a groundwater collector, resulting from the withdrawal of the water.

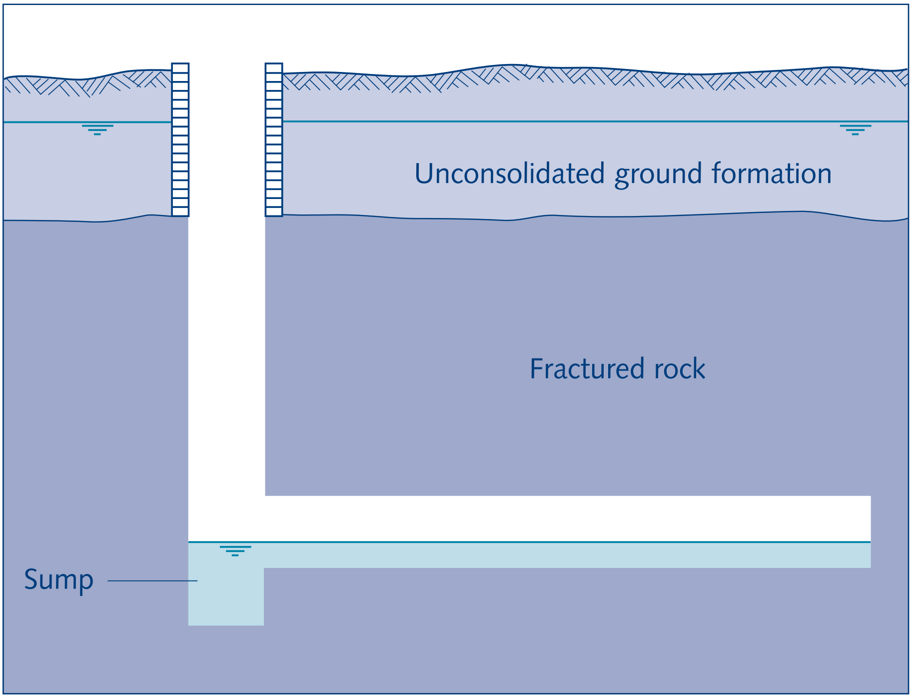


Fig. 10.8. Infiltration tunnel

Vertical means

The vertical means of groundwater withdrawal may be subdivided into large-diameter dug wells (Fig. 10.9) and small-diameter tubewells or boreholes (Fig. 10.10).

Several different well construction techniques exist and the most suitable method for constructing wells in a particular area should be selected carefully. One important factor is the type of geological formation to be penetrated. Table 10.2 provides general guidance on well construction methods. The physical location of a groundwater well is influenced by many factors including hydrogeology, security (to prevent vandalism) and susceptibility to pollution (from pit latrines, flooding, or physical damage). Social requirements, for example easy access for the different user groups and resolution of conflicting demands, also play a significant role in acceptability, use and maintenance.

Dug wells usually have a limited capacity so that their use is restricted to individual household and other small-scale water supplies. The large-diameter shaft acts as a storage reservoir and thus provides for any peak withdrawals. Boreholes should be used when the groundwater table is at a considerable depth below the ground surface, but they are only effective in aquifers of sufficient thickness. The capacity of boreholes varies over a wide range, from less than 1 l/s for small-diameter wells in fine sand aquifers, to over 100 l/s for large-diameter wells in coarse sand or sedimentary rock deposits. Boreholes are very well suited for drinking water supplies because simple precautions will

Table 10.2 Applicability of well construction method

Method	Maximum depth (m)	Diameter (cm)	Geological formation	
			Suitable	Unsuitable
Dug	60	90-500	Clay; silt; sand gravel; soft sandstone; soft, fractured limestone	Igneous rock
Bored	25	5-40	Chalk; gravel; soft sandstone soft; fractured limestone; alluvial formations	Igneous rock
Driven	15-20	3-5	Clay; silt; sand; fine gravel; sandstone (in thin layers)	Any formation with boulders, cemented gravel, limestone, igneous rock
Jetted	80-100	10-30	Clay; silt; sand; pea gravel	Any formation with boulders, cemented gravel, sand stone, limestone, igneous rock
Sludged	50	3-10	Clay; silt; sand; gravel soft sandstone; fractured limestone; alluvial formations	Any igneous rock formation
Percussion-drilled (cable tool)	300	10-60	Clay; silt; sand; gravel; cemented gravel; boulders (in firm bedding); sandstone; limestone; and igneous rock	None
Rotary-drilled (fluid circulation)	250	10-60	Clay; silt; sand (stable); gravel; cemented gravel; sandstone; limestone, and igneous rock	Problems with boulders
Rotary-drilled borehole (down-the-hole air hammer)	250	10-50	Particularly suitable for dolomite; basalts; metamorphic rocks	Loose sand, gravel, clay, silt, sandstone

be adequate to safe-guard the water against contamination. Sometimes, a battery of boreholes in series can be pumped as one unit (Fig. 10.11). Because of the large differences in withdrawal capacity of boreholes and wells, and the fact that withdrawing water from a borehole needs a handpump or other pumping device, the choice between the two options is best made with those who will use and sustain the facility.

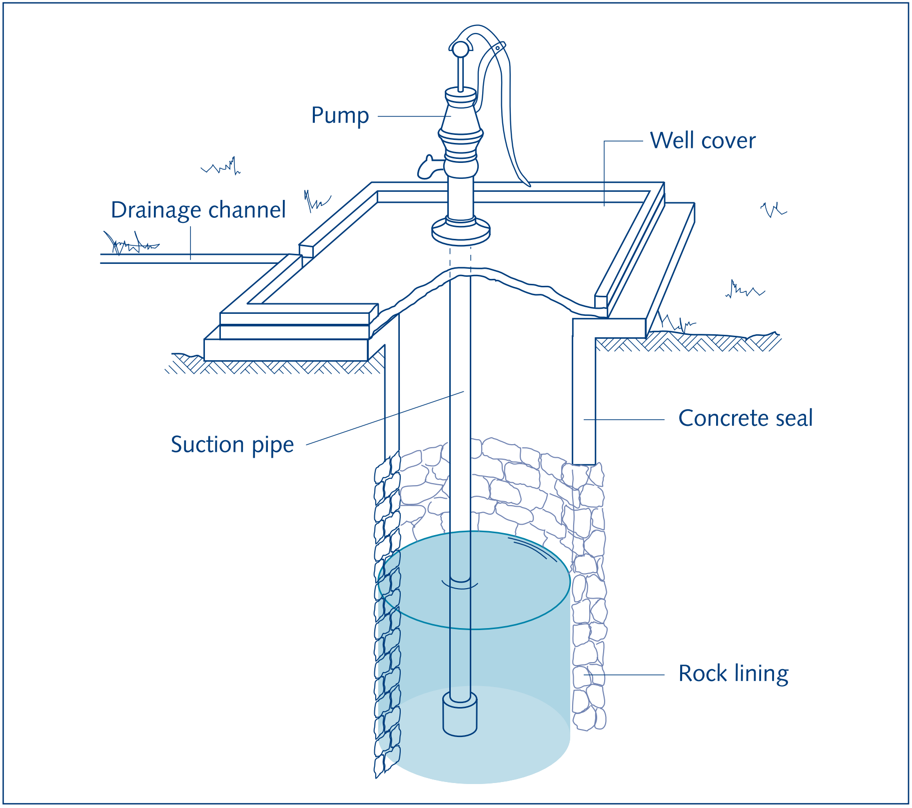


Fig. 10.9. Dug well

In situations where a thick water-bearing ground formation is present at shallow depth, either vertical or horizontal water collectors, or a combination of these, can be appropriate. The technical feasibility will largely depend on the local geological conditions. A much more difficult situation exists when groundwater has to be withdrawn from a thin aquifer situated at a considerable depth. In view of the small saturated area of such an aquifer, boreholes should not be used. Ditches and drains are not appropriate since they would require an excessive amount of excavation work. Sometimes, in consolidated ground, tunnels may be suitable. For unconsolidated ground, radial collector wells may be considered (Fig. 10.10). However, such wells require specialist design and construction and they are, therefore, generally less suited to small-scale water supplies.

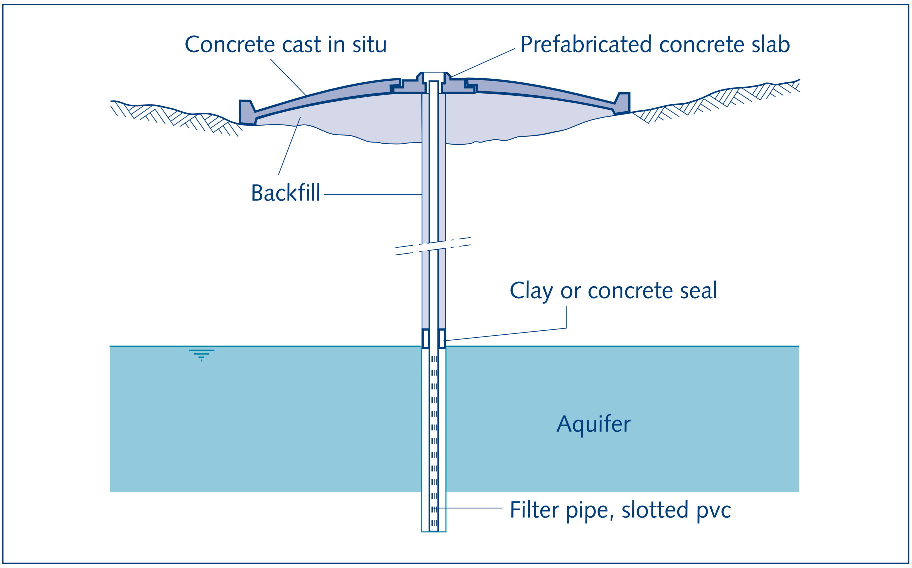


Fig. 10.10. Borehole

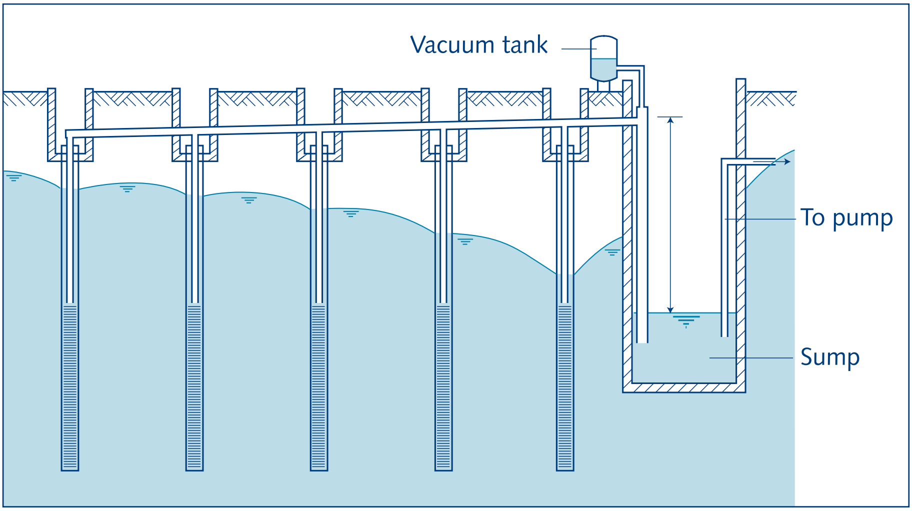


Fig. 10.11. Battery of boreholes

When groundwater is withdrawn there is always a lowering of the groundwater table. In principle, all other withdrawals from the same aquifer are influenced. The effect of groundwater withdrawals for community water supply is usually not great but for the high-rate withdrawals that are frequently made for irrigation purposes, the possible effect of an appreciable lowering of the groundwater table should be carefully investigated. It may be necessary to carry out a test pumping to provide a basis for estimating the future drawdown of the water table (Fig. 10.13). In areas where motor pumps for irrigation are becoming common, safety areas may also need to be planned and managed by the community.

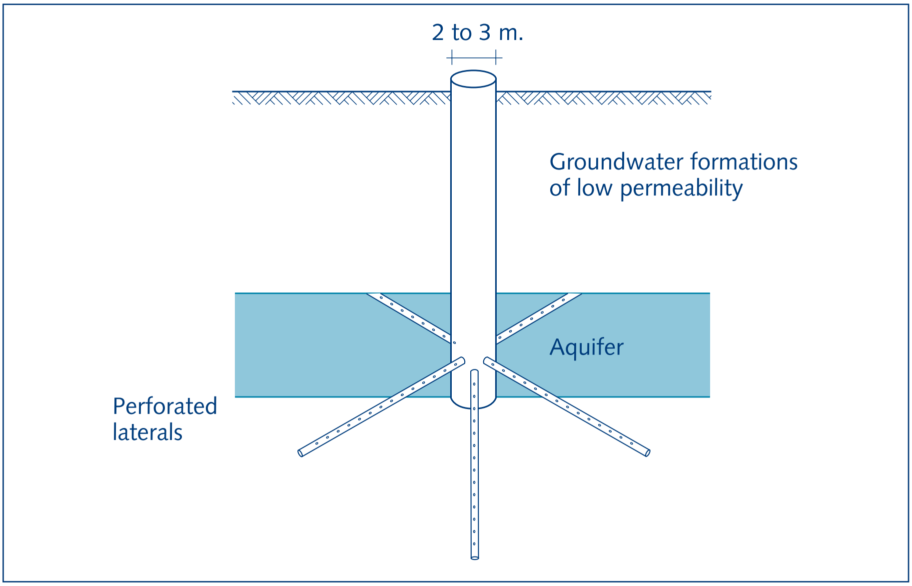


Fig. 10.12. Radial collector well (also called "Ranney Well")

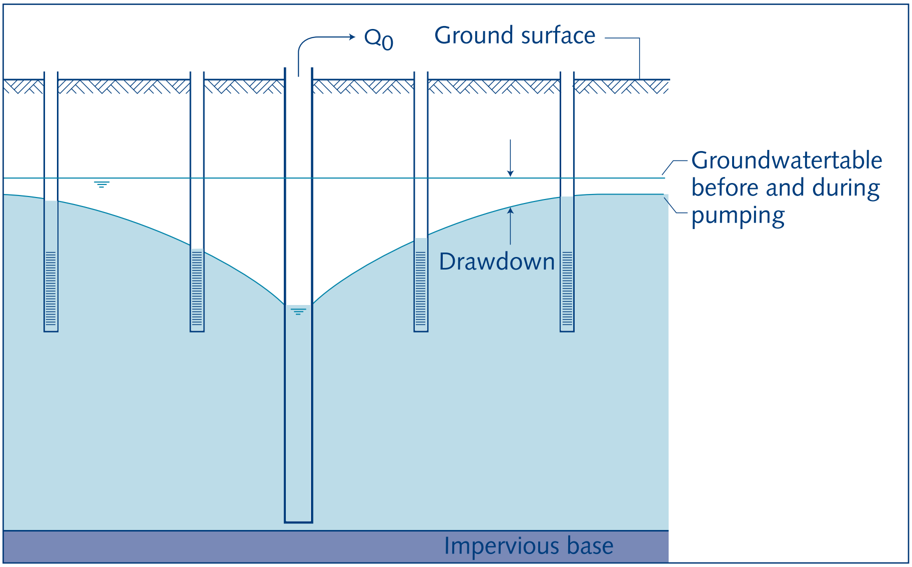


Fig. 10.13. Test pumping

10.4 Infiltration galleries

Ditches for groundwater withdrawal are just a cut in the ground to make the aquifer accessible from the surface. They are easy to construct either manually or with mechanical equipment. The design will also present few problems. The most important requirements are the following (see Fig. 10.14):

- The width and depth should be sufficient to ensure that the collected water flows at a low velocity (usually less than 0.1 m/s) so as to prevent erosion of the ditch sides and to limit the head losses.
- The depth should be greater than 1.0 m and preferably 1.5 m to reduce any penetration of sunlight into the water where it would stimulate plants and algae to grow and cause resistance to the flow of the water.
- The ditch sides should slope gently to provide stability. This is particularly important for the ditch side-water surface contact area.
- For deep ditches, a horizontal embankment about 0.5 m above the normal water level is desirable to facilitate access for cleaning and maintenance work.

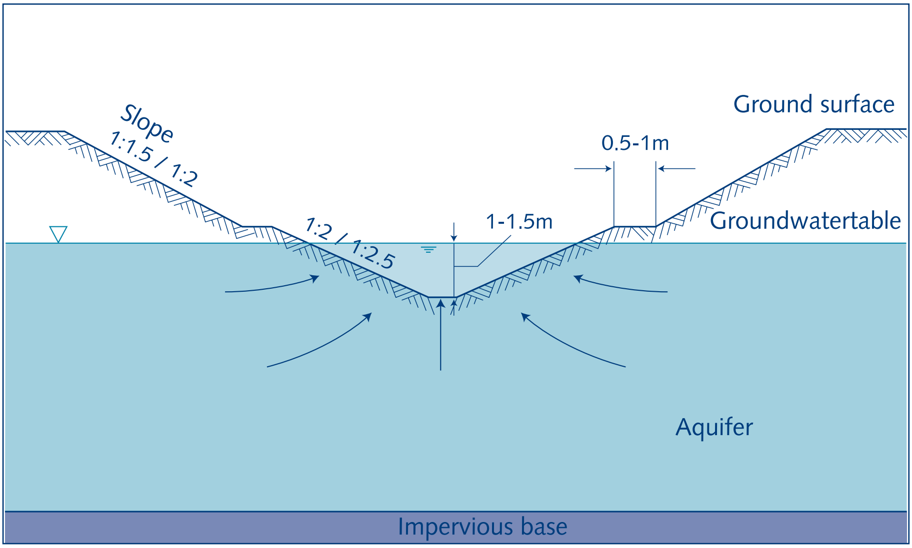


Fig. 10.14. Design of seepage ditch

Seepage ditches being open, the groundwater collected in them is subject to pollution, bacterial contamination and algal growth.

Drains (Fig. 10.15) have pores, perforations or open joints allowing the groundwater to enter. Porous drains may be made of materials such as clay or no-fines concrete (using a pea-size gravel and cement mixture, without sand). Perforated drains are mostly of vitrified clay baked in a kiln, or made of plastic or wood. Drains with open joints are usually made of concrete.

The choice of material for a particular drain construction depends on the required strength, the corrosion resistance needed for the type of groundwater to be collected, and above all on costs and availability. Perforations in the drain need only be made all round it when the drain is placed completely in the aquifer. For drains laid in the upper part of an aquifer, perforations in the underside will be adequate and for drains deep down in the aquifer only upward-facing perforations are needed.

In coarse ground formations such as gravel, the drain openings can easily be made small enough to keep back the ground material. In fine and medium-sized sand, perforated drains and drains with open joints should be packed in one or more layers of gravel or coarse sand, to prevent the fine sand of the aquifer from entering the drains. The outside layer should be fine enough to keep back the aquifer material; the inside layer has to be of a size that is somewhat larger than the drain openings. For an aquifer of sand with an effective size of about 0.2 mm, the gravel pack could consist of two layers, each about 10 cm thick, with grain sizes of 1-2 mm and 4-8 mm. Drain openings about 3 mm wide may then be used. When drains with open joints of 10 mm are used, a third gravel pack layer of 15-30 mm grain size is necessary.

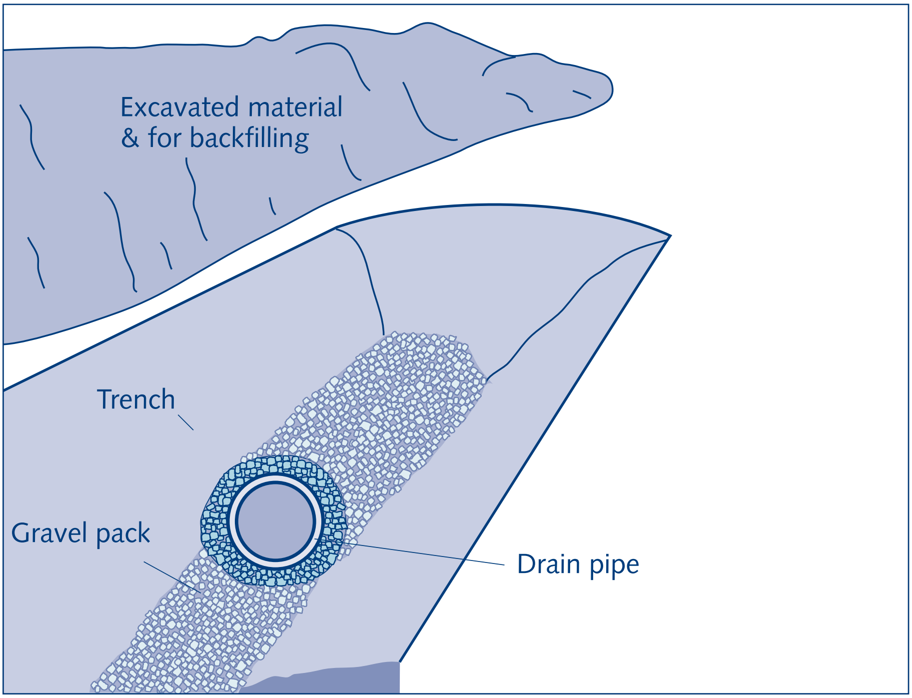


Fig. 10.15. Drain construction

The most important factors in the design of a drain are the internal diameter of the drainpipes, and the depth at which the pipes and gravel pack are placed below the groundwater table.

In spite of the gravel pack, some suspended matter may get into the drain. If this material is allowed to accumulate it will block the drain. To prevent this, the drains should be so sized that the flow velocity is sufficiently high to flush out any silt deposits. For drains to be self-cleaning, the velocity should be higher than 0.5 m/s but it should not be more than 1.0 m/s, or friction losses will be too high. This would cause an uneven drawdown and withdrawal of groundwater along the length of the drain. To accommodate the accumulating quantity of water collected and flowing through the drain, it may be necessary to provide incremental sizes of the drain along its length.

To keep down excavation costs, the drains should be laid no deeper in the ground than necessary. However, the drains must remain fully submerged in the groundwater with the top of the gravel pack at least 0.5 m deep, even at the end of a long dry period when the groundwater table is likely to be at its lowest level. Using the existing groundwater table as a basis, the designer should allow for an operating drawdown of at least 1 m, plus a further drop of the groundwater table of 1 m under dry conditions. The top of the gravel pack thus should be at a depth of 2.5 m or more under the existing water table. If communities contribute voluntary labour, they will need to know about the required minimum depths and the reasons. A simple measuring tool in the shape of an inverted T helps local committee members monitor the proper depth and width of the trench. When iron and manganese is present in the groundwater, there is a serious risk of iron and manganese deposits clogging the drain openings and gravel pack. It is then necessary to lay the drains deeper, some 4-5 m under the existing water table, to prevent oxygen from penetrating to the drains and forming the iron and manganese deposits.

10.5 Dug wells

Dug wells are made simply by digging a hole in the ground. They are widely used in many countries and can be quite satisfactory if conditions are right. Usually no special equipment or skills are required for their construction.

Experience shows that the diameter of a dug well should be at least 1.2 m if two men are to work together at the bottom of the well during the digging. For a well serving a single household or a small community this minimum diameter is usually adequate but when more people are dependent on a dug well, a larger well, 2-3 m in diameter, must be provided. Further increasing the size of a well is seldom useful since the additional water yield so obtained is likely to be very small.

Due to their large diameter and volume, dug wells provide both groundwater withdrawal and storage. Because of the storage capacity, water can be temporarily withdrawn at a higher rate than the recharge inflow into the well. The storage effect is particularly important when the users take the water mostly at peak rates during a few hours in the morning and the evening. Dug wells have also the advantage that users can still get access to the water through the manhole in case the pump breaks down. These and the next points are important aspects to consider with the representatives of male and female user groups during technology choice.

The depth to which a well can and should be dug largely depends on the type of ground and the fluctuation of the groundwater table. Important factors are the stability of the ground and the costs of digging. Private wells are generally less than 10 m deep. Dug wells for communal use are frequently much deeper; 20-30 m is not unusual and depths of 50 m and more have been achieved.

Most dug wells need a lining. For this, various materials are used such as brick, stone, masonry, concrete cast in a shuttering inside the hole, or pre-cast concrete rings. The lining serves several purposes. During construction, it provides protection against caving and collapse and prevents crumbling ground from filling up the dug hole. After completion of the well it retains the walls. In consolidated ground (e.g. rock) the well may stand unlined but a lining of the upper part is always to be recommended (Fig. 10.16). In unconsolidated ground formations the well should be lined over its entire depth (Fig. 10.17). The section of the well penetrating the aquifer requires a lining with openings or perforations enabling the groundwater to flow into the well.

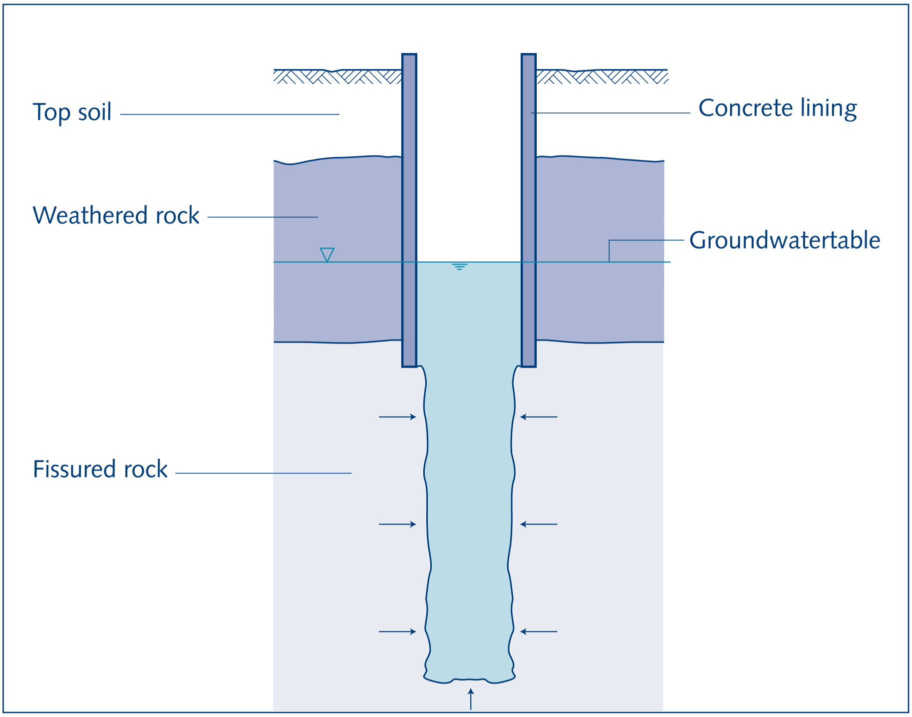


Fig. 10.16. Dug well in rock formation

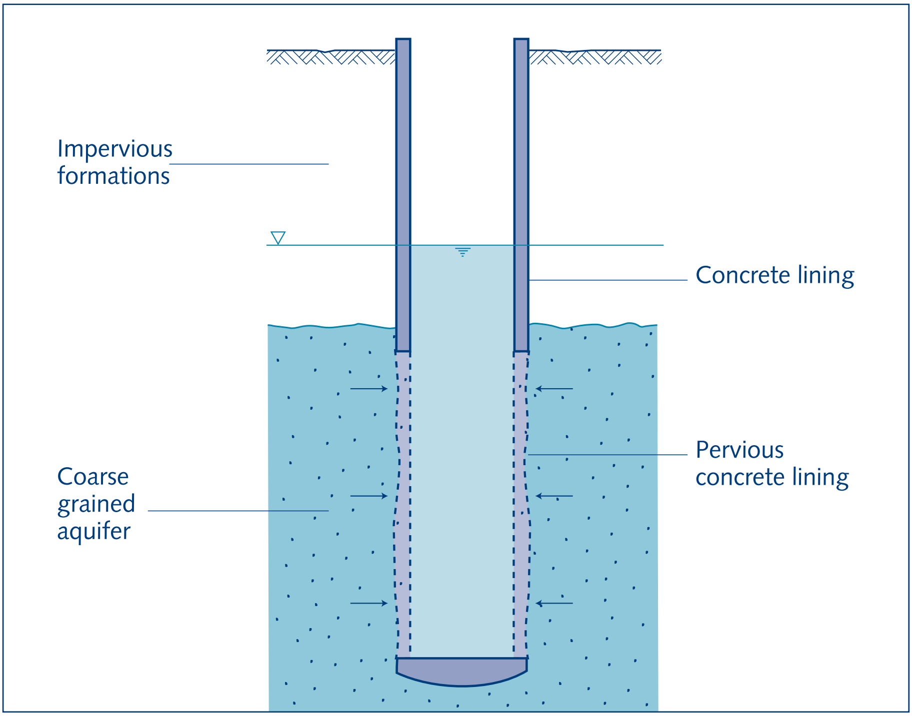


Fig. 10.17. Dug well in coarse granular material

In fine sand aquifers it is impossible to provide a lining with openings or perforations small enough to retain the fine sand and prevent it from passing into the well. In such cases the lining is frequently extended over the entire depth of the well without any openings or perforations. The groundwater enters the well only through the bottom, which is covered with several layers of graded gravel keeping down the fine sand of the water-bearing formation (Fig. 10.17). For example, three layers of graded gravel, each 15 cm thick, may be used with grain sizes of 1-2 mm for the deepest layer, then 4-8 mm, and 20-30 mm effective size at the top.

Lining a dug well will also provide a seal against polluted water seeping from the surface into the well. This is not so effective if the well is open, because the water in it will then be polluted anyway, especially if the water is drawn using buckets and ropes. As a minimal provision, the well lining should be extended at least 0.5 m above the ground to form a head wall around the outer rim of the well. A concrete apron should then be constructed on the ground surface, extending about 2 m all around the well. The concrete apron also seals any fissures between the well lining and the walls of the excavated hole and so prevents polluted surface water from seeping into the well.

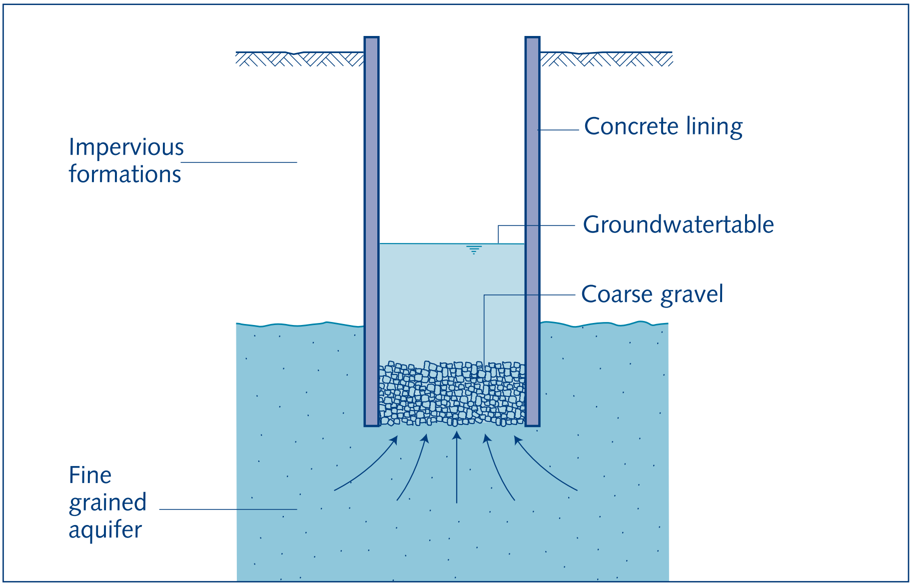


Fig. 10.18. Dug well in fine granular aquifer

All these measures only have a limited effect if the well remains open. A well cover reduces direct contamination by dust and unwanted objects but the bucket and rope will still contaminate the water body. This can be reduced when users decide to clean the well site regularly and even pave it, say with shells, and see to it that the rope and bucket do not trail in the mud but are hung on a bucket stand when not in use.

Full protection of the bacteriological quality of the water from a well can, however, only be obtained if the well top is completely sealed with a watertight slab on which a pump is mounted to draw the water (Fig. 10.19). A manhole that can be tightly and securely locked should be provided to allow disinfection of the water in the well by chlorination. Although simple in itself, the sealing of dug wells is not always feasible; particularly where the standard of pump installation is poor and maintenance requirements cannot be adequately met. Therefore, discussions with local men and women are needed on water quality protection and sanitary measures for the direct well environment against water and soil pollution.

Dug wells are sometimes constructed in a temporary excavation, drained and braced against caving as necessary (Fig. 10.20). Any type of building material may be used. For economy, strength and stability circular walls are to be preferred. Masonry and brick-work are widely used; (reinforced) concrete is also popular, pre-fabricated or cast on the site. When burnt bricks are used, the possible negative impact of the use of local firewood on the environment and on women's work in fuel collection has to be considered. Open joints are used at intervals in masonry and brickwork linings, to enable the groundwater to flow into the well. In concrete linings short pieces of tin tube or garden hose can be cast to provide openings. To avoid the entrance of polluted water from the ground surface, backfilling should be done with care in thin layers that are firmly compacted.

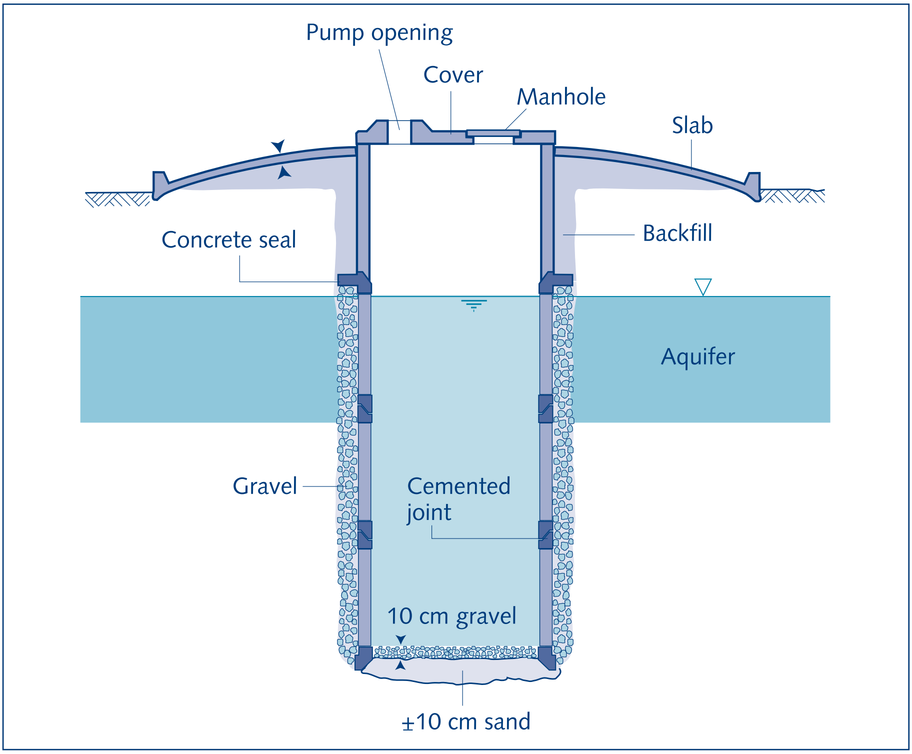


Fig. 10.19 Dug well sealed for sanitary protection

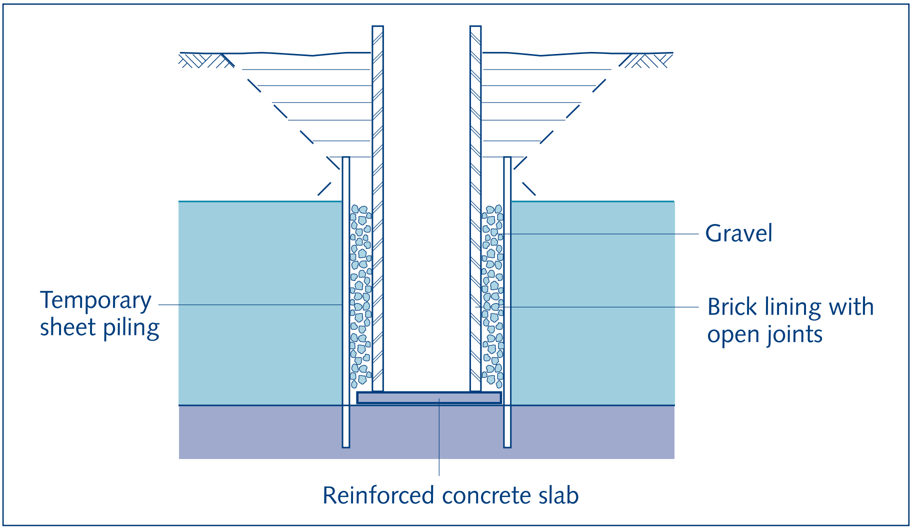


Fig. 10.20. Dug well built in temporary excavation

Stiff consolidated formations requiring no immediate support for stability allow the temporary excavation to be executed as an open hole with unsupported walls. However, it is prudent to carry out the digging section by section as shown in figure 10.21.

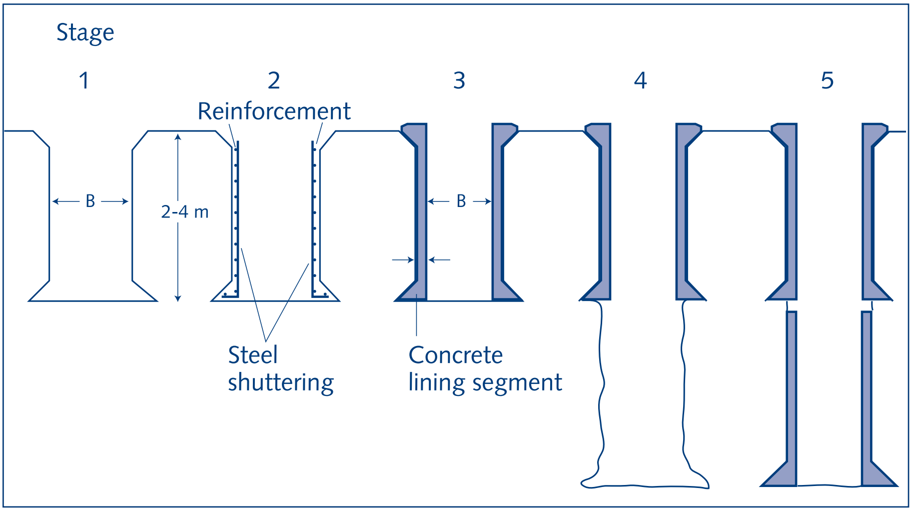


Fig. 10.21. Reinforced concrete lining built on site

Each section should be 2-4 m high and is kept in place by the surrounding ground pressing against it. The most common method of constructing a dug well is by excavation from the inside, removing the ground at the bottom. The lining then sinks down due to its own weight (Fig. 10.22). For wells of a diameter up to 3-4 m the digging frequently is carried out with hand tools. Below the groundwater table de-watering of the well becomes necessary to enable further excavation to be carried out. In this construction method, circular well shapes are mostly used because they settle readily and are not liable to deformation when the well lining sections are subjected to uneven forces.

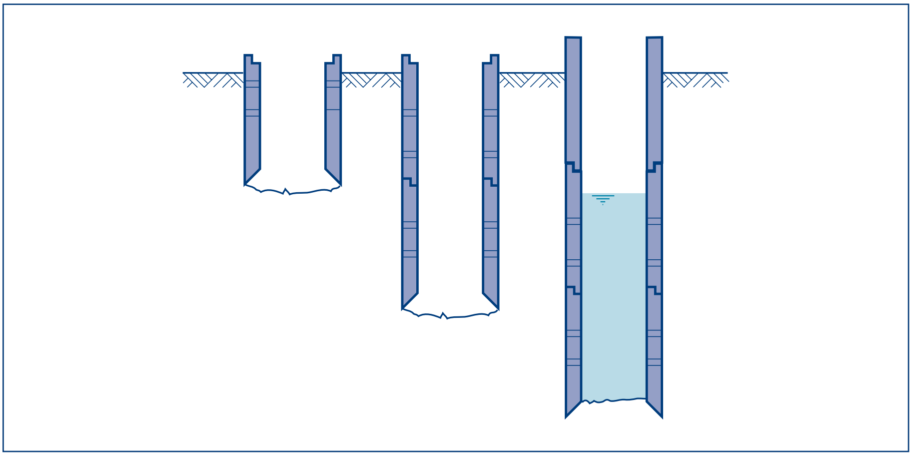


Fig. 10.22. Sinking a dug well by excavation from the inside

Masonry work of stones, bricks or concrete blocks can be used to build the well lining using a strong steel shoe as the base (Fig. 10.23). The shoe prevents the lining from settling unevenly, which could cause deformation and cracks. Reinforced concrete obviously is a more suitable construction material in this respect. It also allows the well lining to be constructed above ground as the well sinking progresses. Large-diameter pipes of concrete or plastic may be used for well lining material. When these are not available or are too expensive or difficult to handle, prefabricated concrete rings may be employed to form the lining (Fig. 10.24). There is no valid reason why prefabricated concrete rings should not be widely used. They require no special materials or skilled masons and need only aggregates and simply trained unskilled workers to cast them. The necessary sand and gravel may usually be obtained in the neighbourhood of the well site.

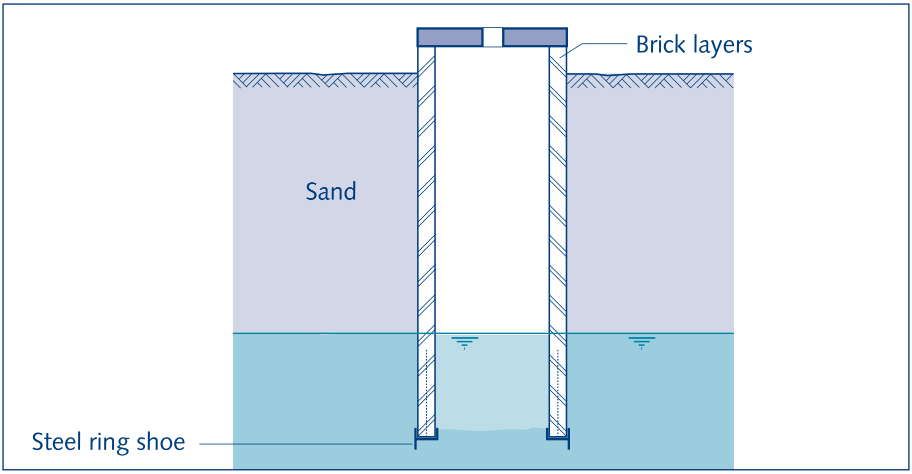


Fig. 10.23. Dug well with brickwork

The lower end of the starter ring is provided with a shoe having an inside cutting edge; the outside diameter is somewhat larger to facilitate the sinking and to reduce ground friction along the outside (Fig. 10.25). The starter ring during sinking leaves a space around the lining. In loose formations this space will be self-sealing but in cohesive formations it must be filled with cement grout or puddled clay as a safe-guard against seepage of polluted water from the ground surface. Over the depth of the aquifer, the rings are made of no-fines concrete (pea-size gravel and cement, without sand) through which the groundwater can enter the well.

Frequently a more economic and technically better construction may be obtained by combining the two methods of construction described above. The construction of figure 10.26 gives an excellent protection against any ingress of polluted seepage water from the surface; it also allows the well to be made deeper when after some time the groundwater may fall to a lower level. The design shown in figure 10.27 does not have this advantage but it costs much less to construct.

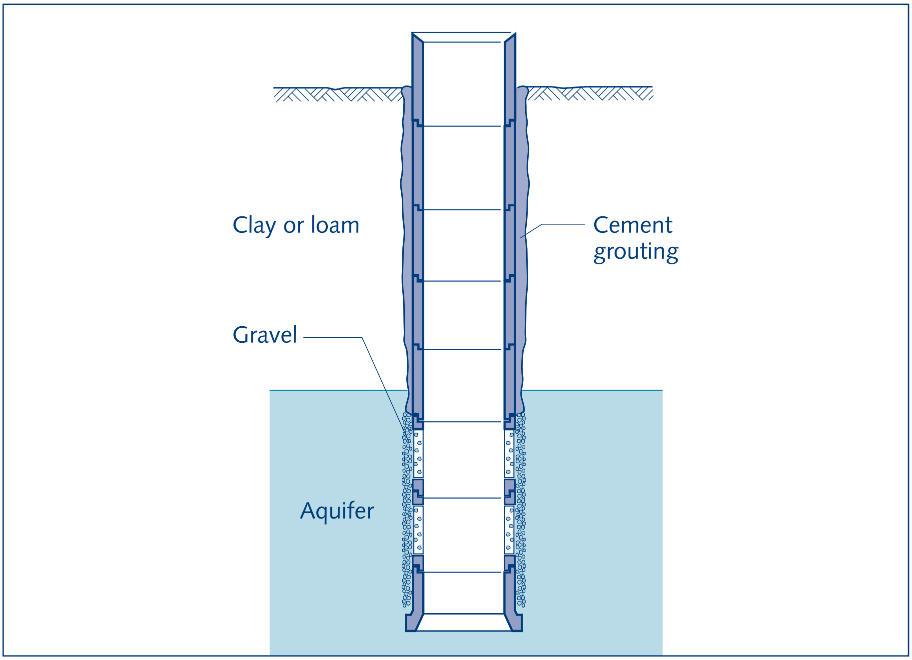


Fig. 10.24. Dug well construction with prefabricated rings

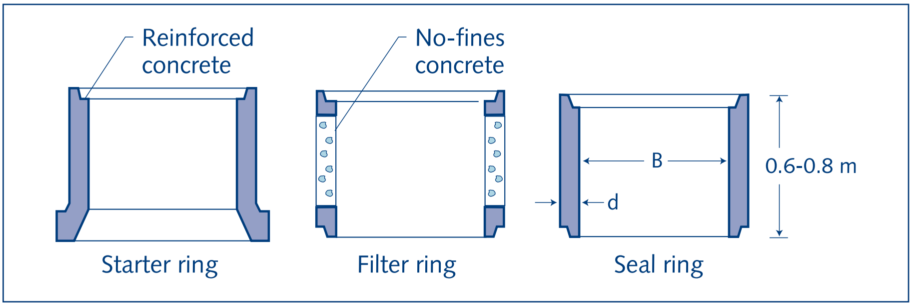


Fig. 10.25. Prefabricated concrete rings

It will be clear that it is not so easy to protect the water of a dug well against bacterial contamination. To sum up, the following precautions are recommended:

- The upper part of the lining should be water-tight preferably to a depth of several metres below the lowest drawdown water level in the well.
- The space between the walls of the dug hole and the lining should be sealed with puddled clay, or better with cement grout.
- The top of the lining should extend some 0.5 m above ground level and should be topped with a watertight cover on which a (hand) pump is to be mounted for drawing the water from the well.
- An apron should be constructed around the raised top of the lining (the head wall) about 2 m wide, sloping outwards and with a gutter draining any spilt water away from the well site.

- The water in the well should be chlorinated for disinfection after the well has been completed. This should be repeated at regular intervals.
- Pros and con's of different options are discussed with women and men and when an open well is decided on, they are encouraged to work out and institutionalise a strategy for maximising and preserving good hygiene.

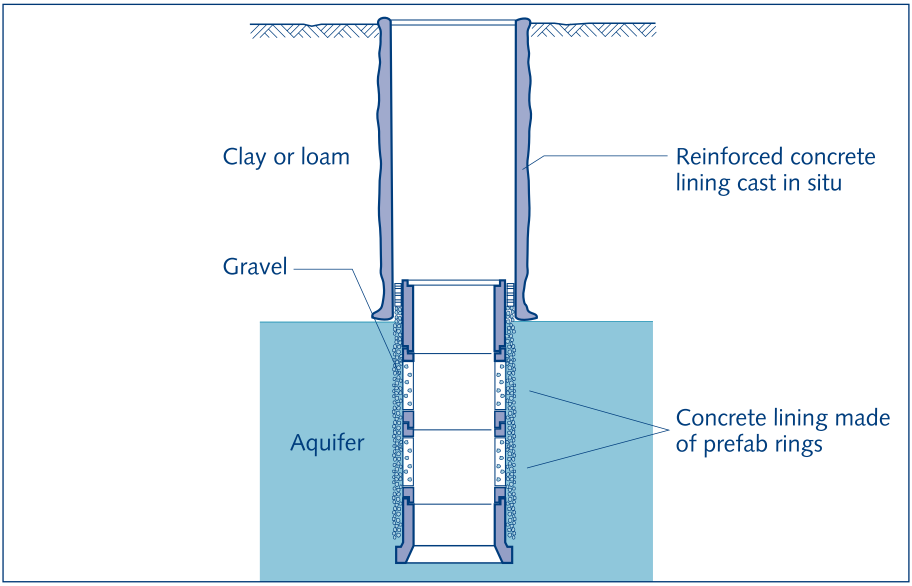


Fig. 10.26. Dug well construction using combination of methods

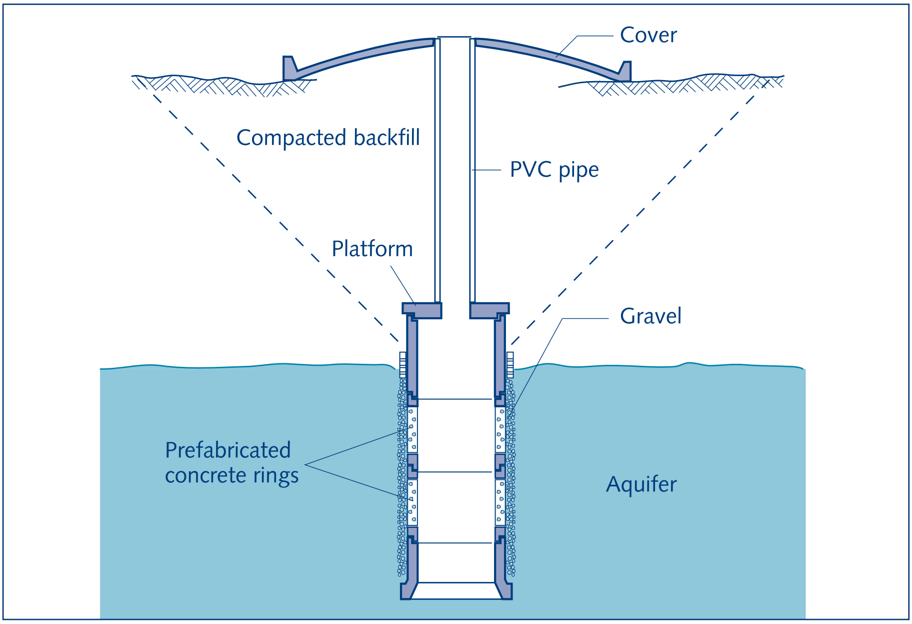


Fig. 10.27. Dug well construction using combination of methods

10.6 Boreholes (Tubewells)

Introduction

A borehole (tubewell) has a casing consisting of pipes (tubes) in the non-water bearing formations, and perforated or slotted screen sections in the aquifer.

Boreholes of small diameter and shallow depth for small capacity water supplies may be constructed by driving, jetting, boring or sludging. Drilling is more versatile and appropriate for larger-diameter boreholes designed for the withdrawal of considerable amounts of water at greater depths, or for tapping aquifers that are overlaid by hard rock or similar ground formations. It does, however, require complicated equipment and specialist drillers with adequate knowledge and experience.

Boreholes can be constructed to 200 m or deeper depending on the method used. Particularly in arid or semi-arid regions, the depth of wells into shallow bedrock and unconsolidated aquifers should accommodate seasonal or annual fluctuations in the water table to avoid drying up in periods of low water table. However, deeper boreholes are more costly to construct and maintain. Drilling norms for particular regions must therefore be established from existing knowledge of drillers and users. There never is a guarantee that water will be found. It is, therefore, important to make full use of any available prospecting and exploration data when choosing the site where a borehole is to be constructed. The assistance of ex-perienced and qualified people is essential, together with the information obtained through hydrogeological surveys.

The completion diameter of a borehole should be optimised taking into account the anticipated yield, the abstraction requirement, the drilling methodology and the type of pumping equipment to be used. For example, a borehole designed for high abstraction urban supply will require a larger drilling and completion diameter (200-300 mm) to accommodate the necessary pumping equipment, to facilitate the higher flow rate, to minimise groundwater inflow velocity and to maximise borehole efficiency. On the other hand a borehole designed for rural handpump supply in which both yield and flow rate are low can be completed at a diameter as small as 75 mm if slim-line pumping equipment is available. In unconsolidated or other unstable formations (boulders, gravel, etc.) several sets of casing of reducing diameter may have to be used to support the borehole as drilling progresses. The requirement to install filter (gravel) pack material alongside screens will also mean increased drilling diameter.

The risk of introducing chemical or biological pollution to the groundwater body via the borehole itself is becoming increasingly important, especially in environments with rapid human development. Installation of an adequate sanitary seal of suitable material between the permanent casing and the natural ground of the borehole wall prevents direct ingress of surface or near-surface pollutants via this relatively open pathway. Flooding or agricultural pollution protection may require special designs.

Borehole construction is greatly influenced by local factors and relatively unknown underground conditions. Several drilling and construction techniques have been developed for use in these different environments. In many cases, the most modern and expensive drilling rig and tools is not necessarily the best equipment. Careful consideration should therefore be given to the degree of technical sophistication of methods adopted and local knowledge considered. A detailed overview of borehole drilling methods is given in annex 2.

Driving

Driven wells (Fig. 10.29) are made by driving a pointed screen (called a *well point*) into the water-bearing formation. To prevent damage to the well point when driving through pebbles or thin layers of hard material, the point at the lower end of the screen is made of solid steel, usually with a slightly larger diameter than the screen itself. As driving proceeds and the well point sinks into the ground, successive sections of pipe are screwed on top so that the upper end of the casing is always above the ground surface. The well point is driven into the ground using a simple mechanism for hitting the top of the pipe. Many arrangements can be used. Figure 10.30 is indicative. Whichever method is used, it is essential to ensure that the blows are square and vertical; otherwise the pipe will bend and perhaps break. As it is the pipe that transmits the blows to the well point, strong thick-walled piping must be used, particularly when difficult driving in hard formations is expected.

In the well driving method shown in figure 10.31, the drive bar falls free inside the screen. The pipe is pulled into the ground rather than driven so that pipe of normal strength classes can be used. Driven wells are especially suitable for soft sandy formations that are readily penetrated by the well point. Driven wells cannot be made in areas where boulders or other obstacles are encountered in the ground. In all ground formations the resistance against driving increases with depth. The application of driven wells is therefore limited to shallow wells of less than 10-15 m depth. For the same reason the diameter is usually small, varying from as narrow as 3 cm to a maximum of about 10 cm, a diameter of 5-8 cm being the most common. Well pumps cannot be installed inside such small diameters. Driven wells also have the disadvantage that the screen openings may become clogged with clay or similar material during the driving. Removing this clogged material is almost impossible after the completion of the driven well.

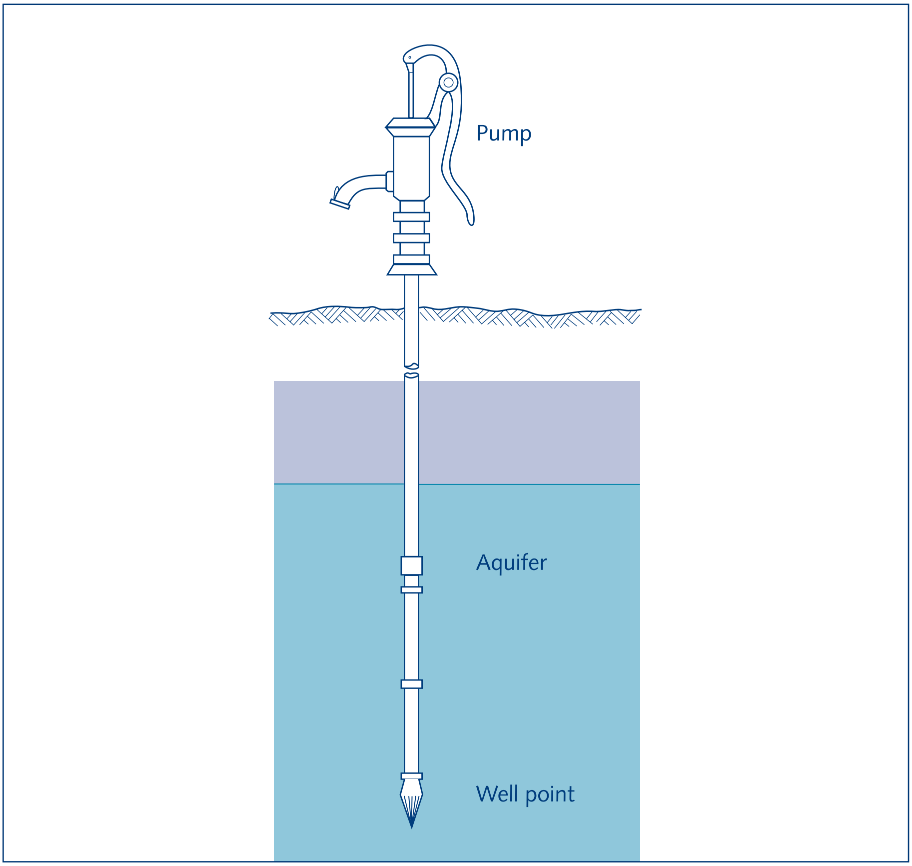


Fig. 10.28. Driven well

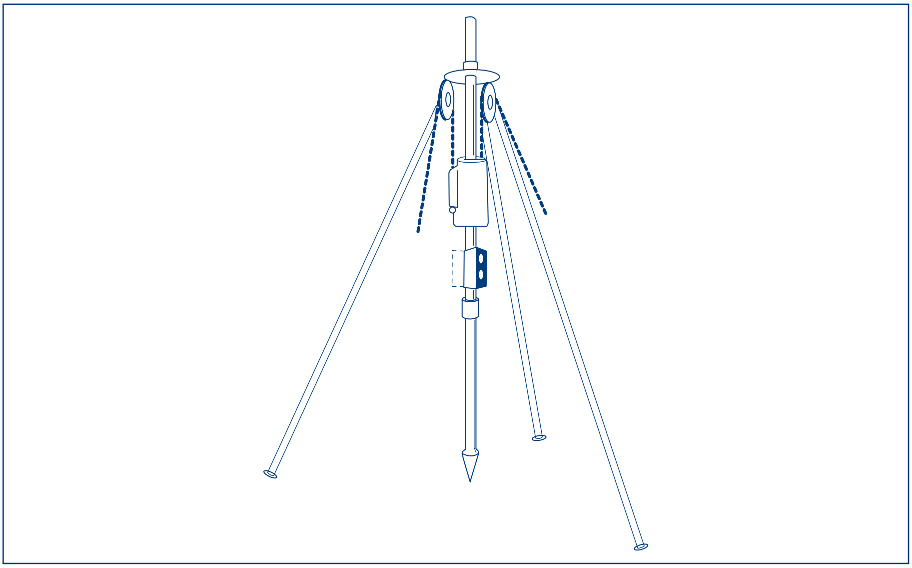


Fig. 10.29. Well driving arrangement

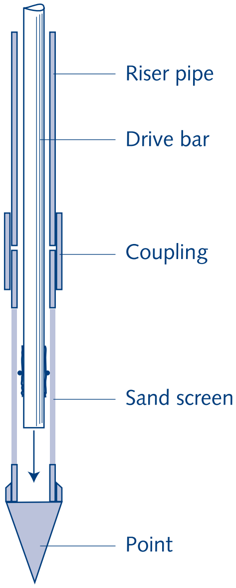


Fig. 10.30. Well driving with inside drive bar

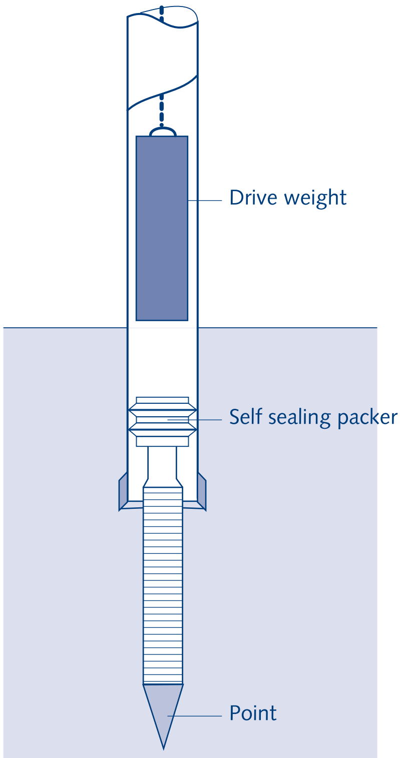


Fig. 10.31. Well drive point with sliding joint

The use of a sliding joint can prevent the clogging of the well screen (Fig. 10.31). During driving the screen is inside the casing and only after reaching the desired depth is it then forced out to intrude the water-bearing formation. When there are hard formations directly below the ground surface, a better solution is to start by boring a hole slightly larger than the well point before driving (Fig. 10.32). When the hole is straight, vertical and deep enough this also helps achieve a plumb well, which otherwise may be difficult to obtain.

If, after completion of the driven well, the inside is thoroughly disinfected, the water from it will be bacteriologically safe and is likely to remain so.

However, the yield from a driven well is usually small, in the range of 0.1 to 1 1/s. This will only be sufficient for private household use or a small community. For a larger supply of water, a number of driven wells may be interconnected with a central suction line and pumped as one unit, but this solution is rather expensive. In rural areas of developing countries driven wells have the advantage of easy and rapid installation with no need for specialised equipment or skills.

Jetting
Jetted wells do not differ much from driven wells but the point at the lower end of the screen is hollow instead of solid, and the well is bored through the erosive action of a stream of water jetting from the point (Fig. 10.32).

Compared with driven wells, jetting of wells is much faster. Mechanical force is not needed so that plastic instead of steel can be used for casing and strainer. Obviously, jetted wells can only be sunk in unconsolidated formations. Sandy aquifers are best suited for this method; clay and hardpan often offer too much resistance to the water jet stream. As with driven wells, boulders cannot be passed but it is a simple process to check the underground formation beforehand by washing the jetting pipe shown in figure 10.33 to the desired depth. Such a jetting pipe is also used in a well jetting technique using a separate jetting pipe to wash the plastic casing and screen into the ground. Compared with driven wells, the depth that can be obtained is somewhat greater, for the same diameter of about 5-8 cm. Clogging of the well screen openings is generally not a problem.

Auger Drilling
Auger drilling (boring) is a totally mechanical method of sinking a borehole. Its primary area of application is for drilling shallow wells in soft and unconsolidated formations such as sand and soft limestone soils, and it is especially appropriate in more clayey overburden that will stand without caving. Mechanical well sinking is an old method of drilling and large-diameter augers were first used over 75 years ago when horses were

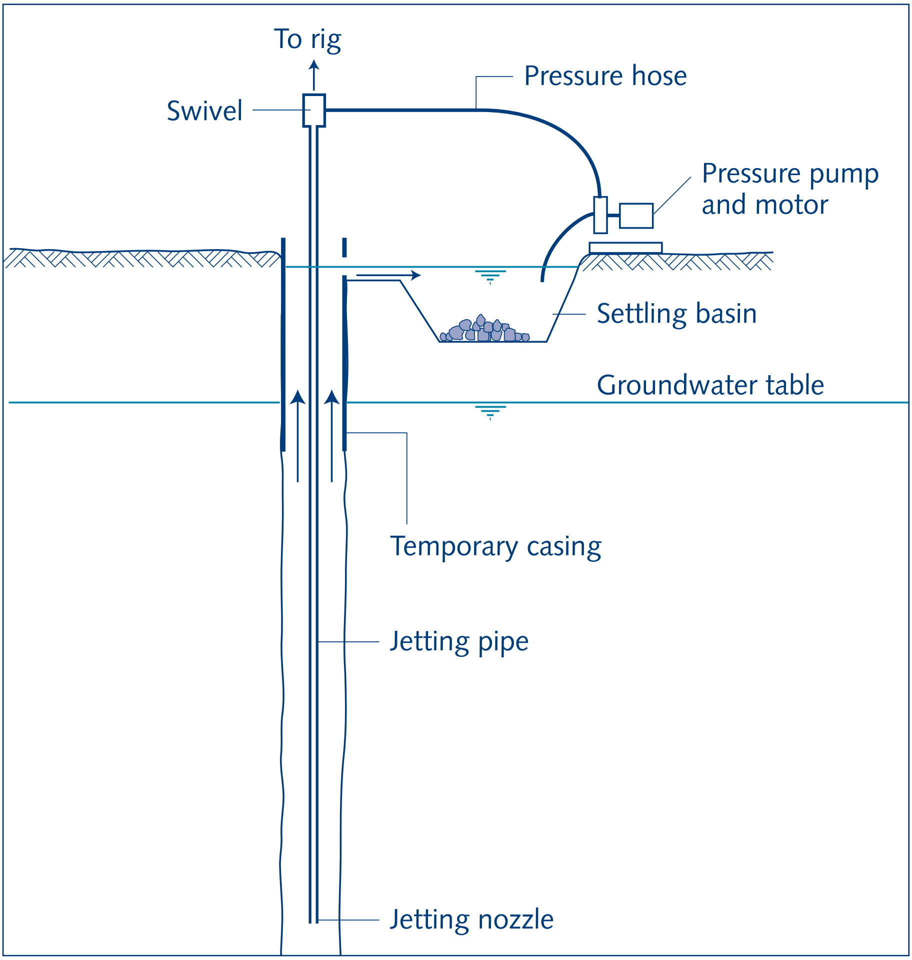


Fig. 10.32. Water jetting

used to provide the motive power. The deepest wells recorded at that time were in the 100-110 m range and were lined with masonry. The auger tools were normally taken down until a caving formation was reached, using an iron or steel *shoe* used to cut a clearance for masonry added at ground level. Auger drilling is not suitable for hard-rock areas, and formations with cobbles or boulders can create difficulties.

The auger is rotated from the surface by means of a drive shaft built up from steel rod sections 3-6 m long and connected by quick-acting couplings. The upper part is called the kelly and has a square cross-section to receive the necessary torque from a rotating table. At the bottom, the auger is provided with a cutting face, which peels the soil from the hole and discharges it into the cylindrical chamber above. When full, the auger is drawn up above ground and the hinged bottom is opened. Each time this is necessary, the drive shaft must be dismantled and coupled together again, a tedious and time-consuming job.

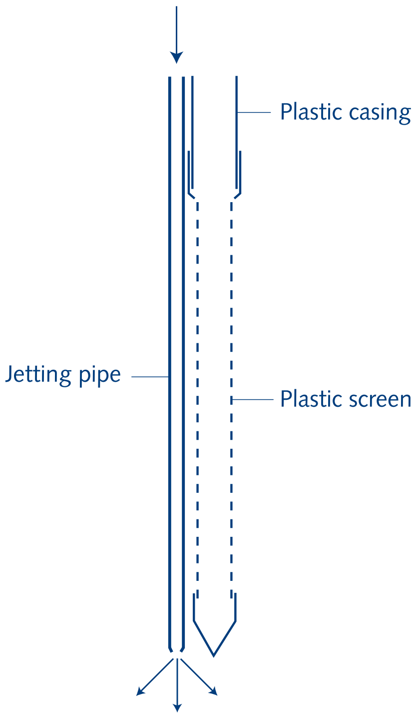


Fig. 10.33. Well jetting with an outside jet pipe

Under the water table, the auger does break up the ground layers but it cannot bring the bored material to the surface as the cuttings escape when the auger is pulled up from the bottom of the hole. A bailer is then lowered in the hole with a cable to collect the cuttings. The bailer is moved up and down near the bottom of the hole; during the down stroke the cuttings are entrapped by a closing valve. The whole operation greatly increases the time required for the boring of a well.

The principal types of auger tools in common use are:

- *Hand auger.* Utilises spiral augers for shallow depth and bucket-type augers for greater depth (Fig. 10.34). Hand auger drilling is suitable for shallow depths at diameters less than 200 mm, and is especially suitable where labour costs are low and low yield (narrow diameter) handpump boreholes are prevalent.
- *Large-diameter bucket auger.* Utilises a cylindrical bucket with auger-type cutting blades on the bottom, rotated into the ground on the end of a long kelly. As the hole progresses the bucket must be withdrawn frequently for emptying. Bucket augers can drill holes up to 1 m in diameter and can excavate below the water table, but have considerable problems with cobbles and boulders that must be removed using other specialist tools.
- *Solid stem 'continuous flight' auger*. Uses a continuous spiral of hard faced *flights* welded onto a small diameter pipe with individual auger sections joined by solid

hexagonal pins, making the tools non-hollow (hence *solid stem*). A cutter head with hardened teeth or blades some 50 mm larger in diameter than the auger flight cuts ground material, and the cuttings are brought to the surface by the flights that act as a screw conveyor. Continuous flight augers can penetrate rapidly in suitable materials but provide poor formation samples and are unsuitable for use below the water table.

- *Hollow-stem auger*. Appears similar to the solid stem auger, but the flights are welded to a larger diameter pipe such that smaller drill rods can also pass through the centre tube. A plug with attached bit is usually situated in the centre of the cutter head and attached to the internal drill rods that are rotated at the same rate as the outer auger flights. The inner diameter of the hollow stem can be as large as 330 mm and the auger tools can be used as temporary casing whilst a shallow water borehole complete with screens, casing and gravel pack is constructed in the central hollow stem. The depth of penetration of this drilling method is limited to between 15 and 35 m depending on the outside diameter of the augers. This drilling technique is widely used in foundation investigations.

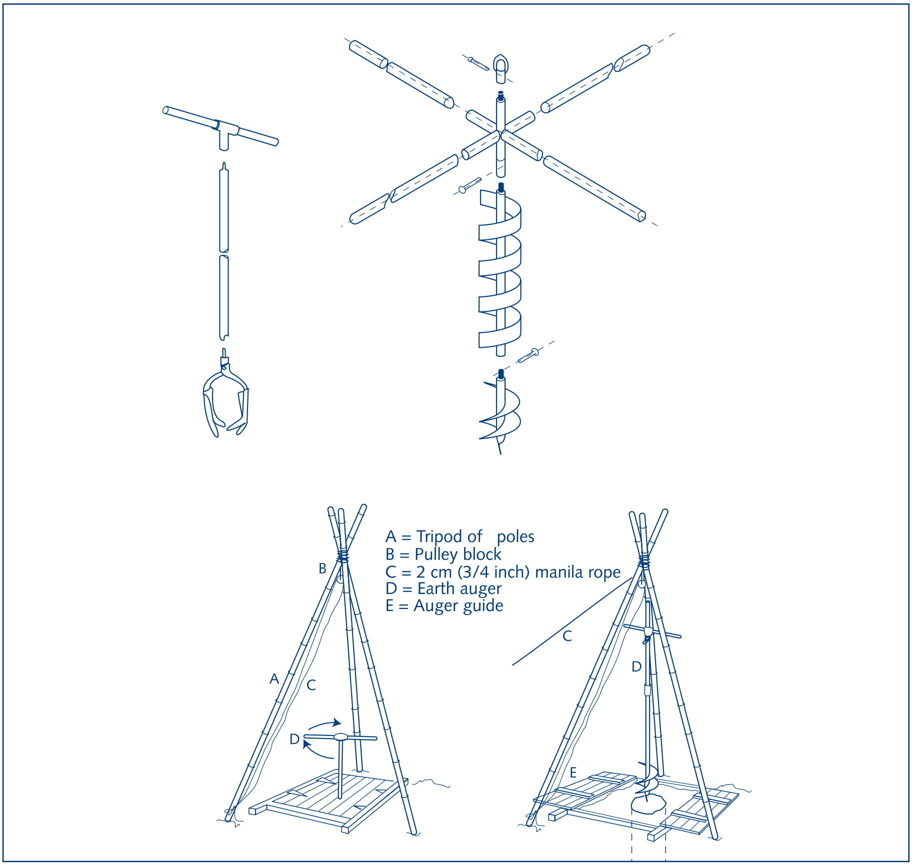


Fig. 10.34. Hand boring equipment

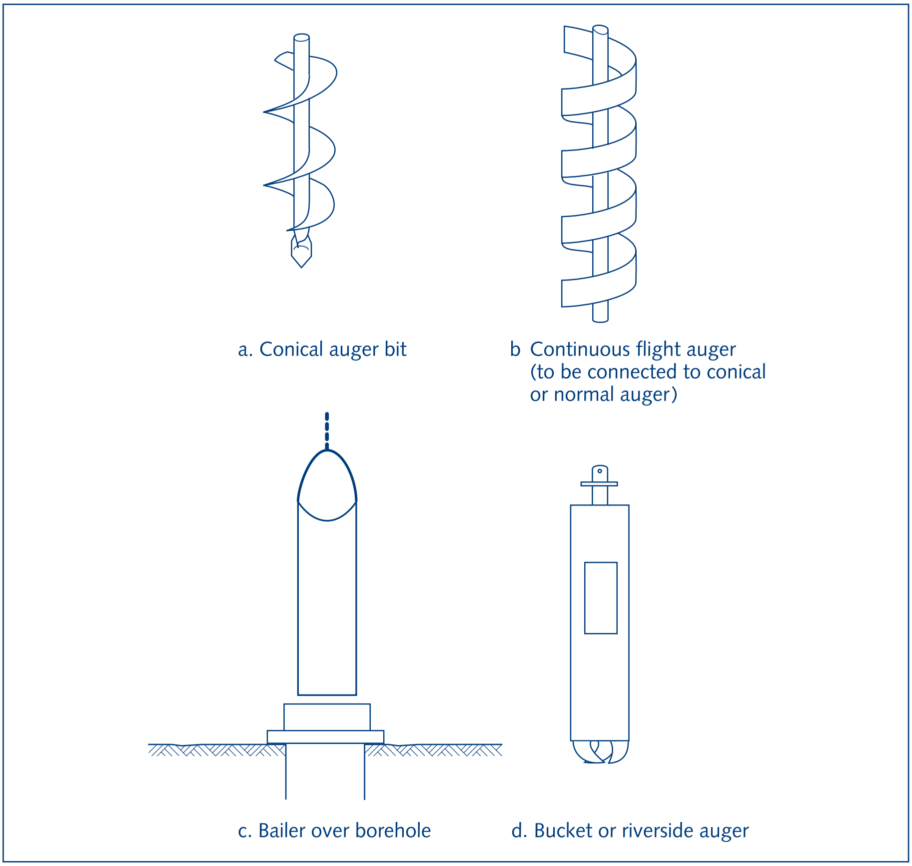


Fig. 10.35. Different auger types

Sludging

The *sludger method* is an indigenous, low-cost, labour-intensive technique for sinking boreholes in unconsolidated alluvial ground formations such as those found in deltaic areas. Boreholes with a depth up to 50 m may be constructed using this method under suitable conditions. In Bangladesh the sludger method has been and continues to be extensively used for sinking numerous boreholes to tap the abundant, shallow groundwater resources present in that deltaic country.

To start the drilling operation, a hole with a diameter of about 0.6 m and 0.5 m deep is made and water is poured into it. Some bamboo staging is erected above the hole. A piece of steel pipe is placed vertically in the soil. The drilling is carried out by moving the pipe up and down with a jerking action while the steel pipe is filled with water. For this, a (bamboo) rafter fastened to the pipe and supported from the staging is operated (Fig. 10.36). At the foot of the drill pipe, soil loosened by the water enters into the pipe, allowing the drill pipe to penetrate into the ground. As a result of the jerking action of the drill pipe, the loosened soil and water is pushed upwards and comes out through the top of the pipe.

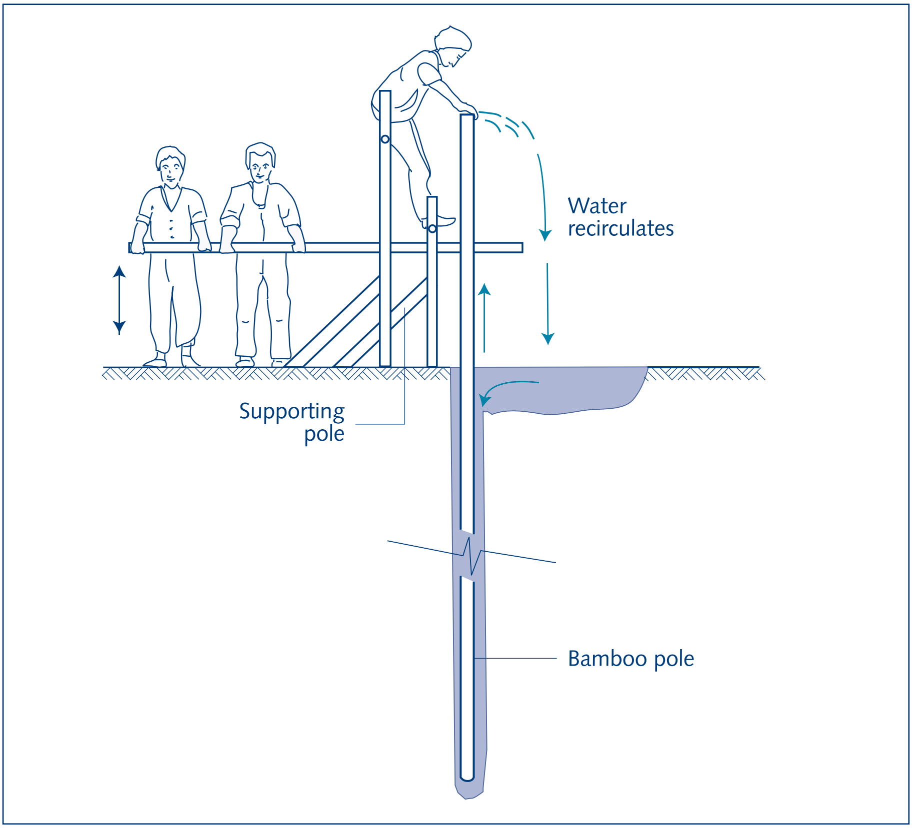


Fig. 10.36. Sludging technique
Source: Waterlines, Technical Briefs, http://www.lboro.ac.uk/well/resources/technical-briefs/43-simple-drilling-methods.pdf

During the well sinking, one man sits on top of the staging and takes care that the hole is drilled perfectly vertically. At each upward stroke, he closes the top of the drill pipe off with his hand, which introduces a suction action. This assists the loosening of the soil at the pipe bottom and the forcing up of the drilled soil. More pieces of pipe are added as the string of drill pipe sections penetrates deeper and deeper in the ground.

As the well sinking proceeds, soil samples are collected from the mudflow coming out at the top of the drill pipe. These are taken at each 1.5 m the drill pipe is sunk further, and then examined. The drilling operation is stopped when good water-bearing formations are penetrated sufficiently. The whole length of pipe is withdrawn piece by piece taking care to keep the drilled hole intact. Immediately after withdrawal of the drill tubes, the well casing consisting of plastic pipes complete with strainer sections is fitted and lowered in the hole up to the determined depth.

An improved version of the sludging equipment for wider application, called the *pounder rig*, has recently been developed and tested in Uganda with good results.

Cable tool percussion drilling

Percussion drilling is one of the two principal drilling methods. It uses a percussive force to break the rock via a hardened drill bit (either by means of lifting and dropping, or by means of an air-driven reciprocating piston). Cable tool percussion drilling is a very old method and was already in use more than 1000 years ago in China. The method basically has not changed, but the tools have been vastly improved. It is practicable for drilling both small and large diameter holes to depths as great as 300-500 m. Cable tool percussion drilling uses relatively inexpensive equipment, but its greatest dis-advantage is that it is very slow.

The principle of cable tool percussion drilling is that a heavy drill bit is lifted and dropped to crush the rock and thus work its way down into the formation (Fig. 10.37). The string of tools consists of a high-carbon steel drill bit (chisel) surmounted by a drill stem (sinker bar), perhaps drilling jars, and a swivel rope socket into which the wire rope is secured.

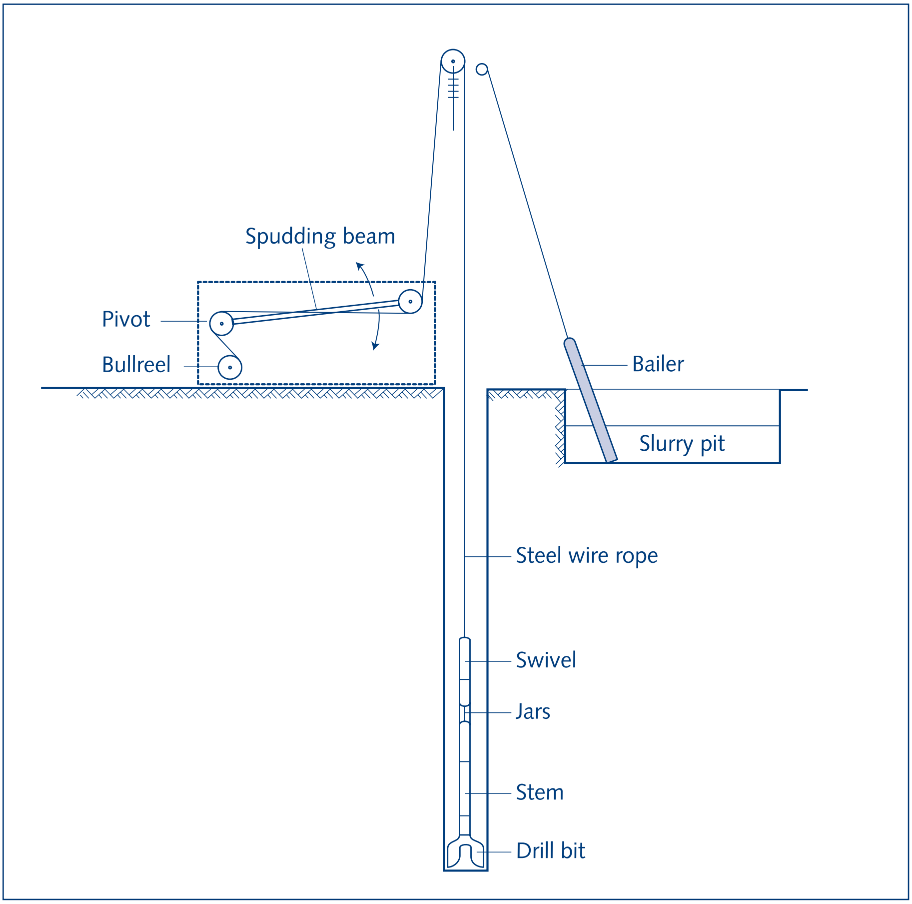


Fig. 10.37. Cable tool or percussion drilling rig

Bits have different shapes depending on the hardness of the formations, and are required to penetrate, crush, mix and ream. The drill stem provides weight and directional stability, and by its pumping action in the borehole it moves the cuttings upward, away from the bit. The tools slowly rotate, moving the bit to a new position on each stroke and ensuring a circular well.

The drilling process, depending on the diameter and depth of the borehole, consists of a column of tools weighing between 300 and 4000 kg reciprocating at 40-80 times per minute at a stroke of between 0.4 and 1.2 m, and slowly rotating. Drilling with a cable tool requires a skilled driller to progress speedily and with the right rotation of the drill bit. Water is fed to the well in small quantities until a natural supply is reached to produce slurry out of the cuttings and to suspend this material above and away from the bit face, but also to cool and lubricate the tool string. The drilling proceeds until the driller feels the thickening slurry retarding the tools, and cleans the hole by lowering a bailer several times. When drilling begins, a short guide tube or conductor pipe is always drilled or hand-sunk in a truly vertical alignment into the ground to stabilise the ground around the working area and to start and maintain a vertical hole. In the past it was common practice to drive casing down to the required depth using a *drive-head* and a *drive-shoe* on the bottom of the casing. However, recovery of temporary (costly) casing was often impossible, even using heavy jacks. The more recent use of flush-jointed temporary casing and less forceful methods of installation has ensured that temporary casing recovery is now the rule rather than the exception.

Down-the-hole (DTH) hammer drilling

The introduction of the air percussion hammer drill marked a significant step forward in the development of drilling tools suitable for constructing boreholes in hard formations. The principal advantages of this method are its speed of penetration and the use of air as a flushing medium to remove rock cuttings from the hole. Typical penetration can be as much as 4-6 m per hour in granite or gneiss, and since no water is required for flushing, this method is especially suited for water-scarce areas.

The air percussion hammer drill works on the same principle as the familiar road drill, with a pneumatic air-actuated single piston hammer operating a cutting bit fitted with hard metal inserts or replaceable 'buttons' attached to the end of a string of drill pipe. Compressed air is circulated down the drill pipe, operating the hammer piston and venting through airways in the bit to carry cuttings to the surface via the borehole annulus.

The bit drills with a frequency of between 500 and 1000 blows per minute. The air is thus driving the piston and is only released through ports in the bit when most of its energy has been expended. The released air now cools the bit, clears the cuttings at the bit face and propels them up the annular space to the ground surface (Fig 10.38).

Hammers with bits of 50-375 mm diameter are widely used, and tools have also been developed to drill up to 750 mm.

A key disadvantage of air percussion methods is that in unconsolidated ground or clays the hammer action is curtailed, the material is simply compressed rather than broken, and penetration is minimal. A minor seepage of groundwater will cause hole-cleaning difficulties since the cuttings will congeal and stick to the wall of the hole, though this can be relieved by the injection of water and surfactant into the air supply.

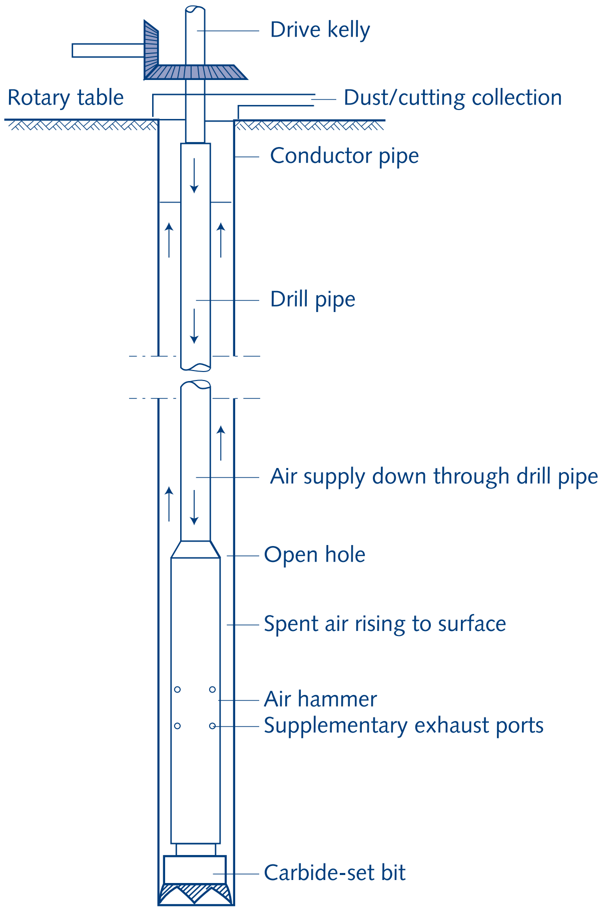


Fig. 10.38. Down-the-hole hammer drill

Direct fluid circulation rotary drilling

Rotary drilling is the second principal drilling method. It relies upon the breaking up of rock material by abrasion and crushing action rather than percussion. The drilling bit is rotated and applies considerable downward force on the rock that grinds down and breaks up the formation. Continuous circulation of a flushing fluid then removes the cuttings and the loosened ground from the hole. Rotary drilling is particularly suitable in loose ground formations and soft rock, and can be used to drill large-diameter holes to considerable depths. The flushing medium is extremely important in this process. It may be air or water with or without additives to increase viscosity.

The principal components of a rotary drilling rig are similar to those of an air percussion rig, with a mast (or "draw-works") used to raise and lower the drill pipes and bit, a rotation mechanism to rotate the drill string and a pumping system to circulate the flushing fluid (Fig. 10.39).

The rotation mechanism may either be a fixed *rotary table* or a *top head drive*, with the latter being more commonly applied in water borehole drilling. In the case of a rotary table rig the uppermost section of the drill string is called the *kelly*. The kelly is of special heavy-duty construction that transmits rotary drive from the rotary table to the drill string.

The drilling fluid, previously clay based or nowadays more usually degradable polymer based, is mixed in a *mud pit* or tank and pumped at high pressure through a flexible hose to the top of the rotating drill string via the kelly. It then flows through the centre of the string to the bottom of the borehole, out through the ports in the bit, and returns to the surface and back into the mud pit via the annular space.

At the bottom of the drill string is the drill bit. The type of bit used depends on the nature of the ground, with drag bits commonly used in unconsolidated or soft formations and roller cutter bits applied in more competent strata. The roller bit is rotated at speeds of 3-30 rpm, depending on borehole diameter and strata. Drag bits carry no rollers but have three or four hard-faced blades and are used to cut soft strata in a manner similar to a wood auger. They penetrate rapidly in soft, unconsolidated materials but tend to stress the drill pipe, over-tighten the tool joints and penetrate very slowly if used in harder strata.

Apart from the common verticality and straightness constraints, rotary drilling requires a continuous weight to be placed on the bit in order to effect penetration. Typically this downward force (*weight*) is within a range of 250-2750 kg per 25 mm of diameter, and is normally applied by the use of *drill collars*. A drill collar is a heavy-walled length of drill pipe that is added to the drill string immediately above the bit, this concentration of weight helping to keep the hole straight and to maintain penetration. The main drill string consists of externally flush drill pipes manufactured of seamless tubing in lengths of between 3 and 10 m. High fluid circulation rates require that the internal diameter through the pipe and tool joints create only minimum friction loss with respect to the descending fluid.

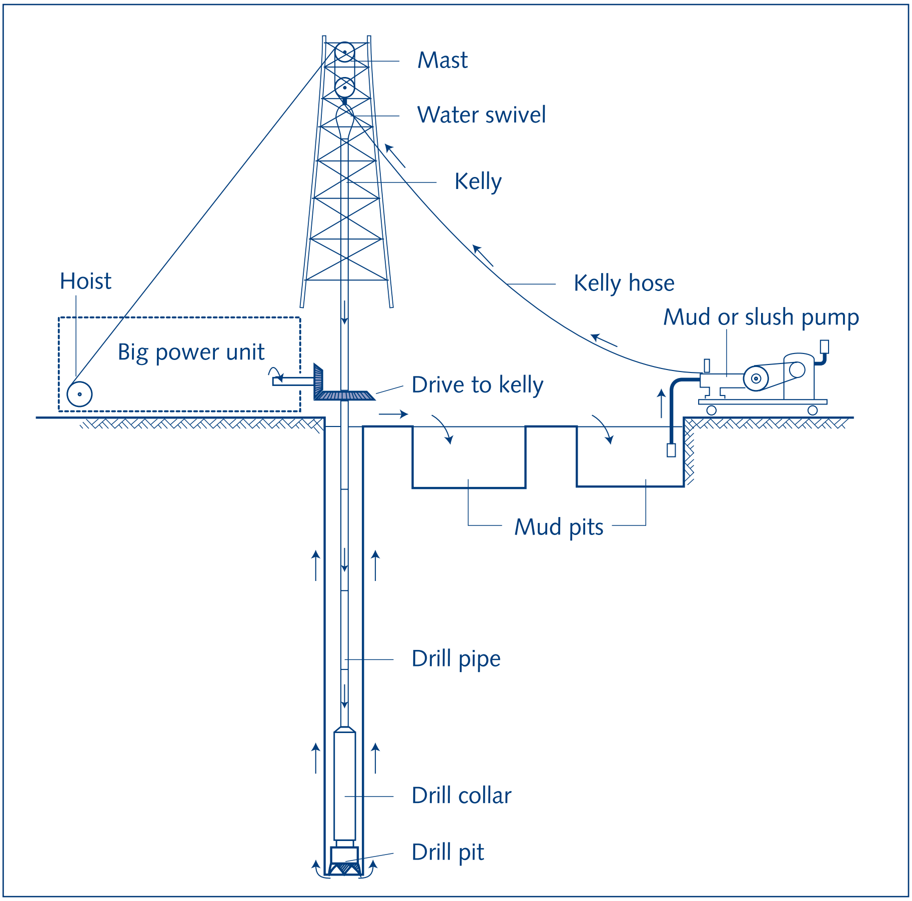


Fig. 10.39. Normal direct circulation rotary drill

Reverse fluid circulation rotary drilling

This method differs from the more common direct circulation system in that the drilling fluid is circulated in the reverse direction. Basically the equipment is similar in general arrangement but considerably larger, and the water way through the tools, drill pipe, swivel, and the kelly is rarely less than 150 mm in diameter (Fig. 10.40). Reverse circulation operates on the basis of "high volume – low pressure", with a relatively high uphole velocity carrying cuttings up the drill pipe and a low downhole velocity generated by flow under gravity in the annular space. The technique is especially applicable to larger-diameter boreholes in unconsolidated materials, with fast penetration, minimal erosion of the borehole wall, representative formation samples and good borehole stability. As a result of the relatively large diameter drill pipe requirements the minimum practical drilling diameter is of the order of 350 mm, and sizes in excess of 1.8 m are not unknown.

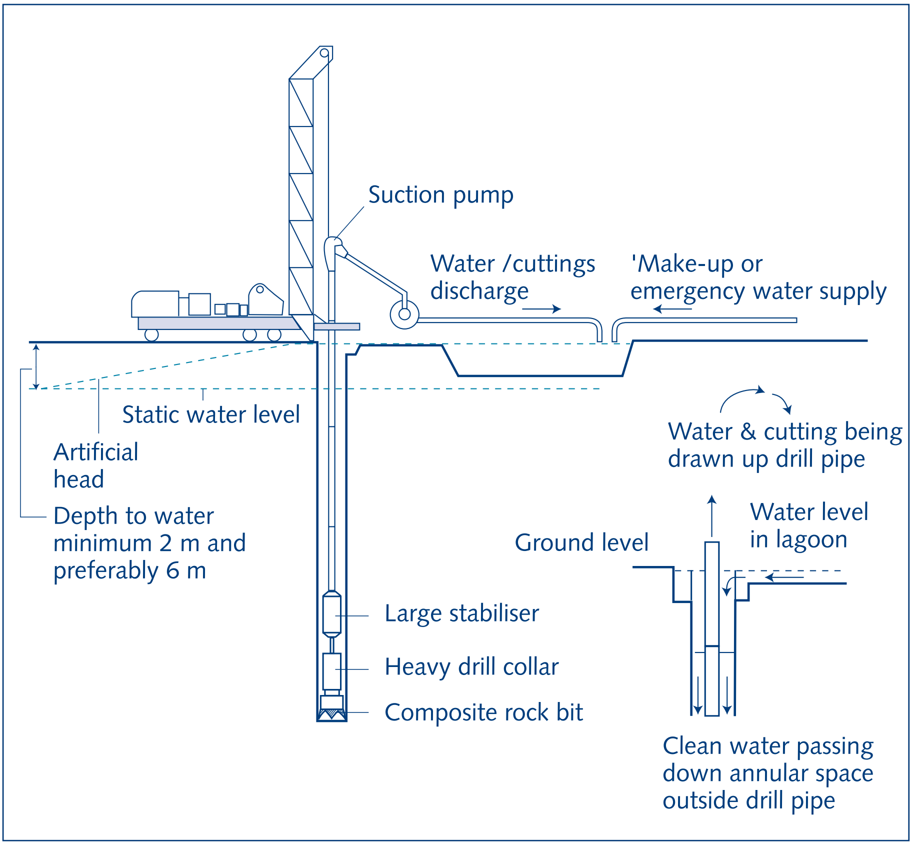


Fig.10.40. Reverse circulation rotary drill

One advantage of the reverse circulation method is that drilling mud is seldom used, with relatively clean water imposed upon the aquifer and therefore no invasion of the formation. Occasionally, low concentrations of polymeric fluid additives are used to reduce friction, swelling of water-sensitive clays, and water loss. In the event of significant clays being drilled in the upper section of the hole, the lagoon should be cleaned out and refilled with fresh water before proceeding into the aquifer, to prevent aquifer invasion.

The main advantage of the reverse circulation method is the very rapid rate of drilling at large diameters, especially in unconsolidated sands and gravel – boreholes are sometimes drilled and lined within 24 hours – as no hole cleaning is necessary. This minimises chances of borehole collapse and possible loss of tools, especially where the head surcharge in the hole to stabilise the borehole walls is small (1-2 m). Under ideal conditions penetration rates of 0.6 m/min have been recorded and average rates of 12 m/hour are quite common. If flanged-and-bolted drill pipe connections are used, they require time-consuming handling and may slow drilling progress.

Return water will infiltrate permeable formations, particularly coarser unconsolidated materials, and will result in water losses from the system. In view of this, one of the prerequisites of reverse circulation drilling is the ready and close availability of a substantial supply of water for make-up purposes. This is often quoted as 45 m^3/h and in practice can amount to between 9 and 70 m^3/h. Fine particles in the return flow that filter out on the walls of the borehole will help minimise these losses, but a considerable quantity of "make-up" water must be available at all times. If water losses are sudden and cannot be immediately made up, the water level in the borehole will drop and caving of the hole walls usually results.

As noted above, the normal reverse circulation system utilises suction as the motive power behind the flow circuit. However, there are circumstances such as pipe friction at greater depths, or a low water table, when suction is insufficient. For this reason most drilling rigs have provisions for introducing an airlift into the system. Providing that drilling has reached a sufficient depth for proper operation of an airlift, this will then induce water within the drill pipe, and the mud pump can be bypassed.

Air circulation rotary drilling

Air circulation has advantages such as longer bit life, faster penetration, and rapid delivery of cuttings to the surface. Air drilling can, however, only be successful in semi-consolidated or consolidated formations in which no assistance is required from the circulating fluid to support the borehole walls.

The drilling equipment is basically similar to that used for conventional fluid flush drilling; one difference is the design of the drilling bit that has air passages to cool the bearings of the bits (Fig. 10.41).

One of the limiting factors when drilling with air, especially as the borehole diameter increases, is the need to produce an adequate uphole air velocity to ensure cuttings removal. To overcome some limitations, several variations on the reverse circulation system have been developed such as dual-wall drill pipes or pipes with built-in air channels. The dual wall method can be used either with DTH hammer and button bits, or with rotary tricone bits.

Dual wall drilling has an advantage of the formation and groundwater samples originating over a very short vertical section before being flushed to the surface without any risk of further contamination. In addition, problems of lost circulation are largely eliminated. The principal disadvantages of this method are its depth and diameter limitations (diameter generally less than 254 mm; depth generally less than 200 m in unconsolidated materials) and the high capital cost of the equipment.

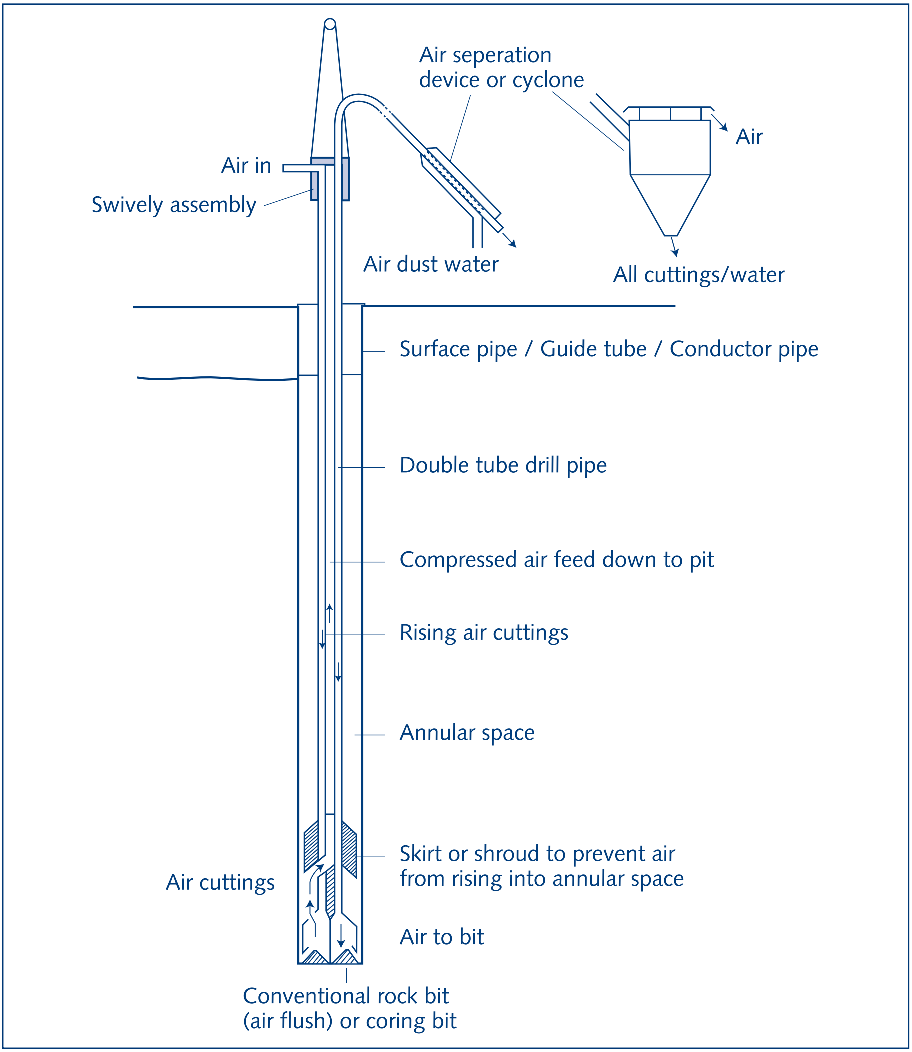


Fig.10.41. Reverse circulation air drilling

Other drilling techniques

Hydraulic tube racking may be used in conjunction with a rig or crane for drilling relatively shallow wells of large diameters in loose gravel, sand, boulders, or similar ground formations. A short guide tube is hand-sunk into the ground and the first of a column of permanent tubes lowered within it. The bottom edge of the column is serrated and the tubes drilled, perforated, or slotted as required. A hydraulically clamped spider with long horizontal rams oscillates the tube column downwards slowly but steadily. When the first tube is close to the spider table, the next tube is placed upon it and the joint welded. Tubes of 450 mm - 1.2 m can be worked down to 30 m or so under the right conditions, the advantage of this system being that there is no need for temporary tubes or large lagoons. There also is no contamination of the aquifer by drilling fluids.

Scow (or California Stovepipe) drilling is applied in cable-tool drilling, and combines the cutting edge of a chisel with the material handling ability of a bailer. The *scow* consists of a heavy, thick-walled bailer with a cutting shoe and a flap valve, suspended by a *scow sub* by means of a pair of reins and a heavy pin from the drilling jar and swivel socket assembly. In operation, it is run into the hole and the normal reciprocating action is applied inside the casing shoe. Water for drilling is added if it is not present naturally. Material is dislodged by the cutting shoe and swept into the body of the scow. The scow is then removed for emptying periodically. Scow drilling can be successfully used in loose, troublesome strata, especially where coarse gravel and boulders occur, and has the advantage of dislodging and lifting the material rather than expending time and power on crushing.

Shell and auger drilling is a percussion technique that uses a string of either solid or hollow rods that are lifted and dropped to provide the cutting action to a chisel bit with a check valve incorporated in the tool. The auger tool is used to cut and remove clay, and the *shell* is similar to a bailer and removes soft strata already loosened by the chisel bit. If hollow rods are used, drilling fluid to assist in removing cuttings can be incorporated in a reverse circulation circuit, with flow down the borehole annulus and return flow through the centre of the rods. This drilling method requires only a lightweight rig and is often used for site-investigation work, since hole diameters are limited to 50-100 mm to very shallow depths (< 20 m).

10.7 Construction materials

During the design of a borehole the selection of the correct materials required for its construction is of extreme importance. In defining the technical specifications of the materials considerations must be given to the expected dimensions of the borehole (depth, diameter) and its ultimate usage, as well as the cost and availability of the materials. Ideally all materials for a borehole, or a complete drilling programme, should be with the contractor prior to commencing the work. The principal borehole construction materials, including those used in drilling as well as those incorporated in the completed structure, are briefly discussed below.

Drilling fluids

Virtually all rotary drilling systems require drilling fluids. The addition of some natural clay to increase viscosity in order to aid the lifting of rock cuttings and gravel subsequently led to the use of the term "mud" for this circulating medium. Nowadays the term "drilling fluid" is more commonly used, and refers variously to clean water, dry air, a suspension of solids or a mixture of liquid additives in water or water, surfactants and colloids dispersed in air.

The primary functions of a drilling fluid are:

- To remove cuttings from the face of the borehole and transport them to the surface
- To lubricate and cool the bit and tool string
- To stabilise the borehole whilst drilling proceeds
- To facilitate suspension of cuttings in the borehole when the fluid is not circulating (e.g. whilst adding additional drill pipe)
- To allow settlement of fine cuttings to the bottom of the settling pits
- To control fluid loss in permeable formations by building up a wall-cake to consolidate the formation and to reduce the loss of fluid into the formation
- To help control sub-surface hydrostatic pressures
- To help provide some buoyancy to long strings of tools or casing in deep boreholes

The most widely used drilling fluid additives are:

- **Clay or bentonite**
  Natural clay or *bentonite* is widely used in water well drilling. Different types of clay may be used, but the only common commercially available clay is montmorillonite or *bentonite*.
- **Organic polymers**
  To overcome the possible aquifer degradation inherent with clay-based drilling fluid additives, organic polymers are now widely used as a clay substitute.
- **Air**
  The ideal drilling strata in which to apply this flushing medium are hard, stable igneous or metamorphic formations when penetration rates can be high. Fissured zones can often be penetrated without the fear of lost circulation associ-ated with water-based fluids.
- **Foam**
  Drilling foam is created when a small volume of water mixed with a surfactant is injected into the air stream. Foaming agents prevent cuttings from aggregating and also reduce the surface tension of water droplets so that both can be lifted more easily to the surface, thus helping to overcome large groundwater inflows. Foam also reduces the uphole velocity requirements, thereby reducing the volume and pressure of air required. Loss of air into the formation and hole wall erosion are thus minimised.

Casing and Screens

Casing used in water boreholes is tubular material that provides support to the walls of the borehole and may be either temporary (used by the driller during drilling of the borehole and subsequently withdrawn) or permanent (forming part of the final construction of the completed borehole). Steel casing is most commonly used, but thermoplastic casing is now increasingly applied in areas of potentially corrosive groundwater and where boreholes are generally less than 300 m deep. Other materials such as glass fibre are also used but are much less common. Selection of casing material should be based upon water quality, borehole depth and diameter, drilling methods, local regulations and cost.

A borehole screen is a filtering device that allows groundwater to enter the borehole. It provides structural support but prevents sediment from entering, especially in unconsolidated strata. Proper screen design and selection is important for the hydraulic efficiency of the borehole, as well as for the longevity and long-term cost of the structure. Screens should have maximum open area to create minimum resistance to flow into the hole, but at the same time must minimise sediment ingress and provide adequate structural strength. Optimising each of these criteria for a particular borehole is the essence of screen design.

Gravel Packs

Gravel pack (or filter pack) is graded granular material placed in a thin zone around the screens in order to increase the effective hydraulic diameter of the borehole and to help inhibit the movement of sediments into the borehole. Clearly, the borehole diameter relative to the final cased completion diameter must be large enough to allow installation of such material, which in turn implies that larger drilling diameter must be employed in holes that are scheduled to be gravel packed. Gravel pack material should be chosen to retain most of the unconsolidated formation material, and screen openings are then selected so as to retain about 90% of the gravel pack. Gravel packs are 100-200 mm thick.

Sanitary seals

In order to prevent ingress to the aquifer of any potential contaminants from the surface via the borehole itself, it is necessary to seal the uppermost section of the annulus between the outermost casing string and the wall of the borehole. The sealing material commonly used is cement grout or a bentonite mixture. It is also prudent to ensure that no potential contaminants can enter the borehole from the surface via the space between any other internal casing strings.

A sanitary seal should preferably be installed in continuity with a cement or concrete well head protection slab to minimise cracking and joints. It is common practice for this slab to be at least 1 m square, with at least 500 mm of its thickness below natural ground level and 300 mm above (Fig. 10.42). The permanent casing protruding through this slab should extend at least 300 mm above the slab, which should slope in all directions away from the casing.

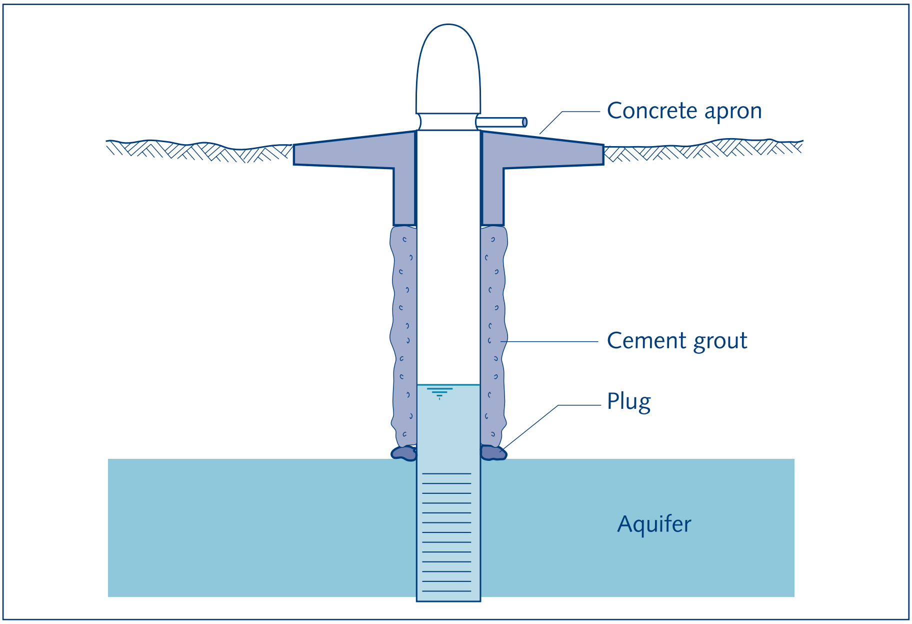


Fig. 10.42 Sanitary seal of borehole

10.8 Borehole development

All drilling methods alter the hydraulic characteristics of formation materials in the vicinity of the borehole. Development procedures are designed to restore or improve these characteristics so as to maximise the performance of the borehole by improving specific capacity and hydraulic efficiency. Other forms of development, often termed *aquifer stimulation*, may be applied after completion of the borehole in order to improve the transmitting properties of the formation in semi-consolidated and consolidated strata. The more commonly used development techniques are outlined below.

Development after completion of drilling

Development of a borehole after completion of drilling forms part of the normal drilling procedure. A number of factors influence the type and potential success of such development, including the well completion configuration (screen slot size, open area, gravel pack thickness and whether a graded or a natural pack is present), the type of drilling fluid used (air or water-based fluids using clays or polymers) and the nature of the formation itself. Development methods include:

Overpumping. This method entails pumping the borehole at a rate greater than that at which it will be pumped in production. This is the least effective method, as it generally only develops the more permeable sections of the aquifer and, since water only flows inwards toward the borehole, it can draw excessive material against the screen openings, creating a condition termed *bridging* in which the formation is only partially stabilised. Formation material may subsequently enter the hole if the formation is agitated and the *bridges* collapse.

Surging. This method flushes water backwards and forwards through the screen, so preventing any bridging behind the screen and moving fines through into the hole. The surge effect can be generated by intermittent pumping and repeatedly allowing the water column to fall back into the hole, or preferably by mechanical means using a close-fitting plunger (*surge block*) moved up and down on the hole by the drilling rig.

Air surging and pumping. This technique uses an airlift pumping action in combination with the surging effect described above. Air is injected into the hole to lift the water column, and then shut off such that the column falls back into the hole.

Jetting. This development method uses the injection of high pressure air or water through the screens to remove fines and drilling fluids. It uses a special jetting tool that directs horizontal jets onto the screens to break up any filter cake and agitate and flush the adjacent gravel pack or formation. This method is most appropriate with rotary rigs.

Jetting and simultaneous pumping. This method combines high pressure water jetting with pumping (usually using an airlift system) and is particularly applicable in unconsolidated sands and gravel. Essentially the jetting process loosens the fine material and the pumping action draws it through the screen and directly to the surface.

In all the development methods noted above the addition of a small quantity of a polyphosphate compound before or during development will assist in breaking up and removing any clay material that may clog the screens or the gravel pack.

Hydro-fracturing

In bedrock aquifers groundwater is contained in fractures and borehole yields are often very low. In such cases the yield may be enhanced by the use of an aquifer stimulation method such as hydro-fracturing. This is a second level of development (of the aquifer) in which high pressure pumps are used to inject fluid to overcome the overlying rock pressure and open up existing and new fractures that will enable water movement into the borehole. Considerable pumping pressure is required.

Supplementary development methods

Other development or stimulation methods include the use of acid injection in carbonate aquifers to enlarge fissures by dissolution of aquifer material, and “shooting” in hard-rock terrain using explosive charges placed in the borehole to increase the number of fractures around the hole. Such methods are very specialised techniques, and are not commonly used in the majority of water borehole drilling work.

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Web sites

HTN Network for Cost-Effective Water and Sanitation Technologies:
http://www.skat.ch/htn/
Water and Sanitation Program: http://www.wsp.org/english/index.html
WatSanWeb: http://www.skat.ch/ws/link/watsan/WW_index.htm
Practica Foundation on low cost drilling techniques: http://www.practicafoundation.nl

Discussion groups

Handpump Technology Network: http://www.jiscmail.ac.uk/lists/htn.html
Water Forum: http://groups.yahoo.com/group/waterforum/