Module 2

The Science of Surface and Ground Water

Lesson
7
Well Hydraulics

Instructional Objectives

At the end of this lesson, the student shall be able to learn the following:

1. The concepts of steady and unsteady ground water flow to wells
2. Mathematical equations for water flow to wells in confined aquifers
3. Mathematical equations for water flow to wells in unconfined aquifers
4. Determination of the physical properties of confined aquifers
5. Design and installation of tube wells

2.7.0 Introduction

As established in the earlier lessons, an enormous amount of water is stored within the ground. A small portion of that is in an unsaturated state but that below the water table, also called ground water, can be easily extracted for useful purpose, depending on the type and location within which the water exists. It has been roughly estimated that of the global water resources, about 0.6 percent exists as ground water, out of which about half can be economically extracted with the present drilling technology. In fact, the ground water is the largest source of fresh water on earth excluding the polar icecaps and glaciers. Hence, ground water has been extracted on all regions of the world for different purposes and about nearly one fifth of all the water used in the world is obtained from ground water sources.

Evidence of extraction of water from dug wells has been found in the archeological remnants of Mohenjodaro. In many of the cities established during the medieval ages in India, the main source of water was dug wells, though people were dependent on surface water bodies like rivers or, lakes, or ponds, if that happened to be nearby. It is only during the past century that tube wells became popular as an easily operatable source of extraction of ground water. Gradually with easy access to electricity deep tube wells have become a common source of water. However, establishment of tube well extraction of water involves knowledge about the movement of water through the geological formations, which has been discussed in Lessons 2.5 and 2.6. Water may have to be extracted from formations ranging from sand, silt, clay, fractured rocks of different compositions etc., A well may be dug to extract water from a confined or an unconfined aquifer. Digging of more than one well in close vicinity affects each others' yield as the drawdown of one influences the other. This may be quantitatively estimated by theories of ground water flow applied to the radial flow of water to each well. In this lesson, these theories are discussed, which would be helpful in designing such wells.

2.7.1 Steady flow and unsteady flows

Imagine a farmer using a deep tube or a dug well as a source of water for irrigating his field. The well may be fitted with a ***submergible pump*** or a ***centrifugal pump*** to draw out water and discharge at the head of a channel leading to the fields. As long as the pump is not in operation, the water in the well remains at a steady at a level, at that of the water table (Figure 1).

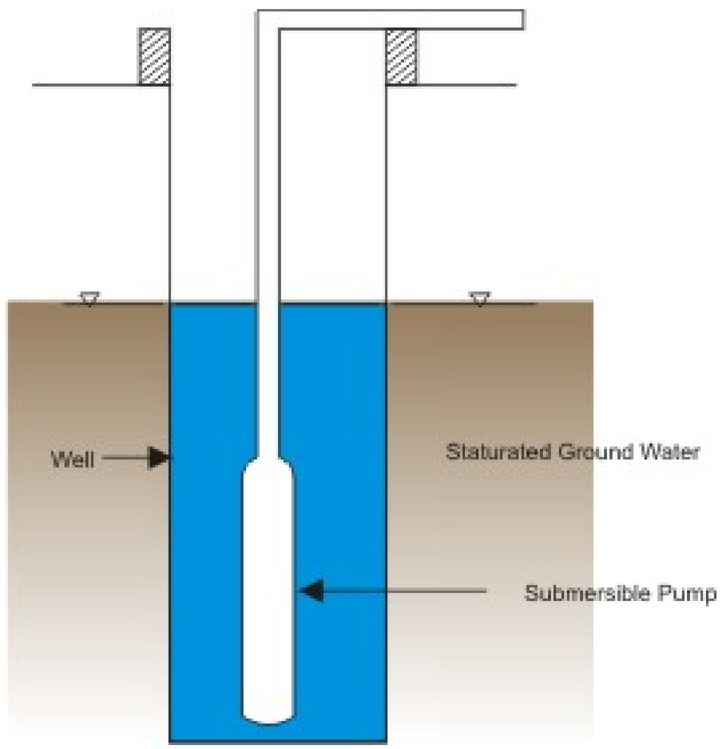

FIGURE 1. PUMP NOT STARTED

When the pump is just started, it starts drawing out water from the well and the level of water in the well decreases. The water table surrounding the well also gets lowered (Figure 2).

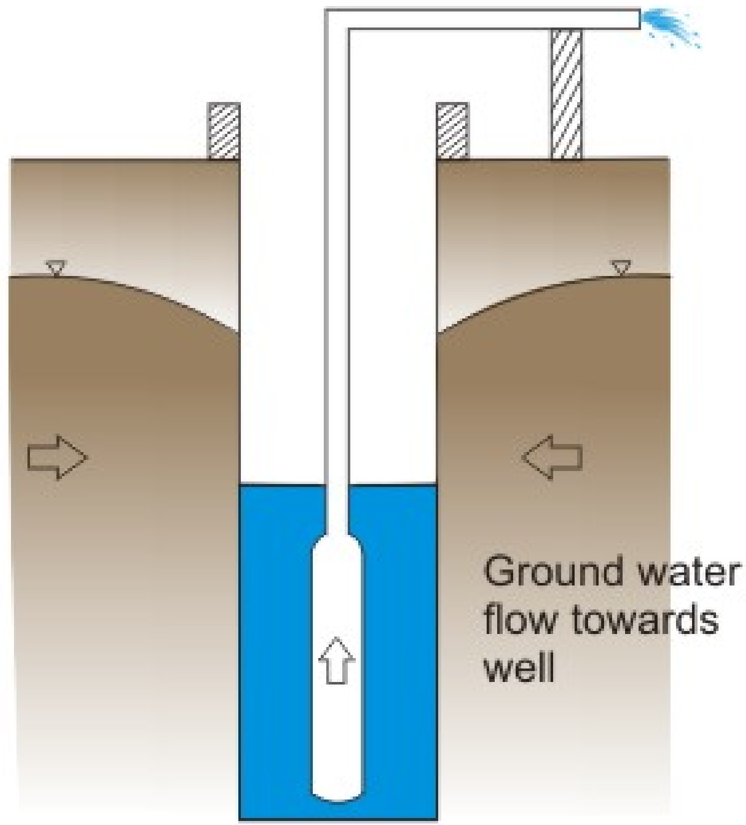

FIGURE 2. PUMP JUST STARTED

The water table gets lowered and forms a conical depression much like that shown in Figure 3.

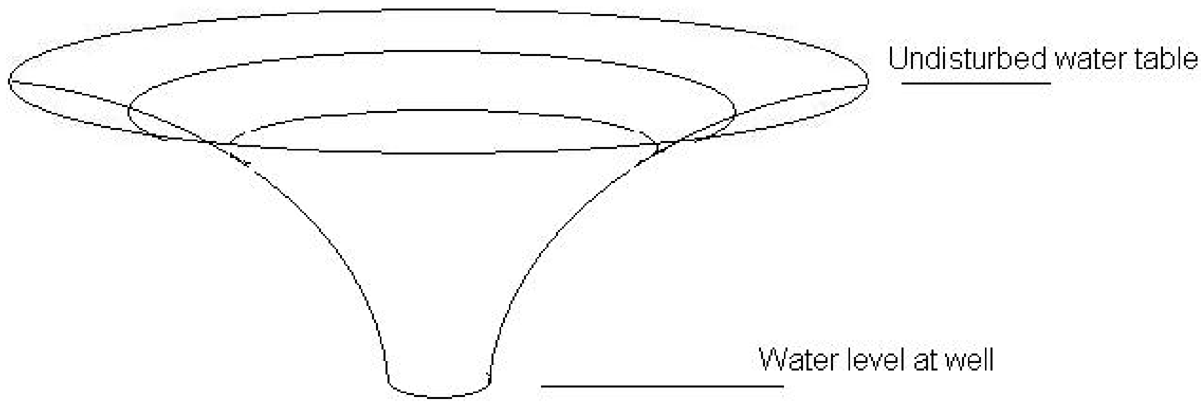

FIGURE 3. Cone of depression

It may be observed that the surface of the water table, shaped now in the form of a cone, is steepest where it meets the well. Farther away from the well, the surface is flatter and beyond a certain distance, called the radius of influence, the surface of the cone is almost as flat as the original water table.

As pumping continues (at the rated capacity of the pump), the water table gets lowered further until it becomes steady. At this position the water surface is called the draw down curve (Figure 4).

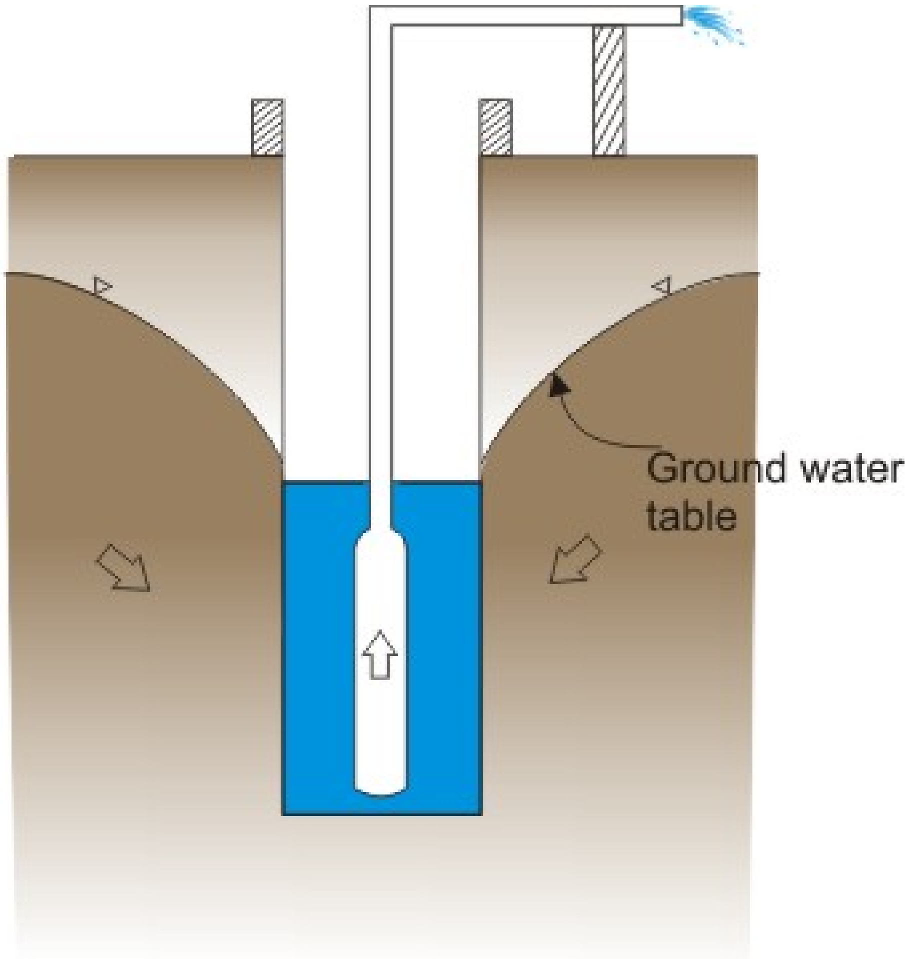

FIGURE 4. STEADY STATE DRAWDOWN

In must be observed that the water that is being pumped up from the well is being replenished by water traveling through the saturated formation towards the well. Further, if the capacity of the pump amount of water being in thrown from aware would be a lowered still.

Figures 1 to 4 depict a well that is drawing water from an unconfined aquifer. Corresponding figure of a steady state draw down curve in a confined aquifer would be as shown in Figure 5.

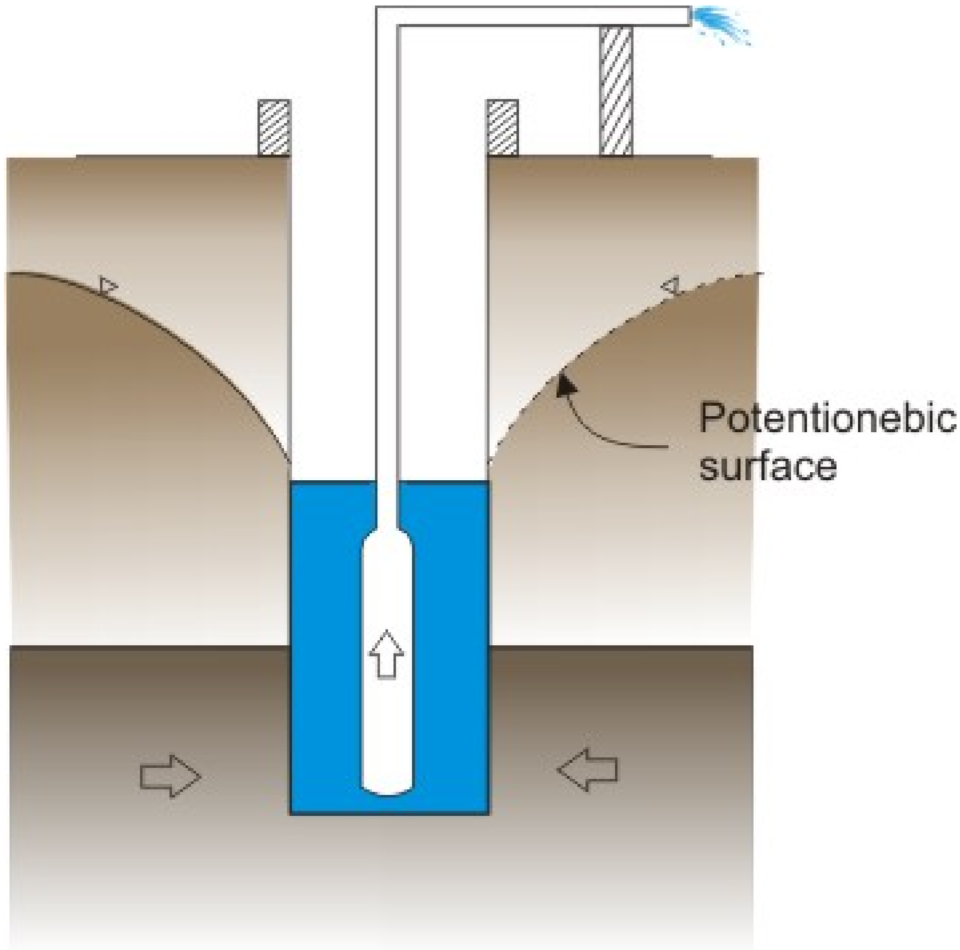

FIGURE 5. STEADY STATE POTENTIONETIC SURFACE FOR CONFINED AGNIFER

The following sections explain the mathematical relation between the water pumped and the location of the draw down. It must be remembered that the flow towards the wells is actually taking place radially. Hence, we shall be predominantly using the ground water flow equations using the cylindrical coordinates (*r*, *θ*, *z*, *w*) in contrast to the ones using Cartesian coordinates (*x, y, z*) as used in the previous lessons.

Steady and unsteady flow situations may further be classified as being confined or unconfined, depending on the relative positions of ground water conveying strata and the water table. The following sections describe each of these conditions individually.

2.7.2 Steady Flow to a Well: Confined Aquifer

Consider the case of a pumped well completely penetrating a confined aquifer (Figure 6). The corresponding steady state piezometric draw down surface is also shown for the assumed constant pumped discharge Q.

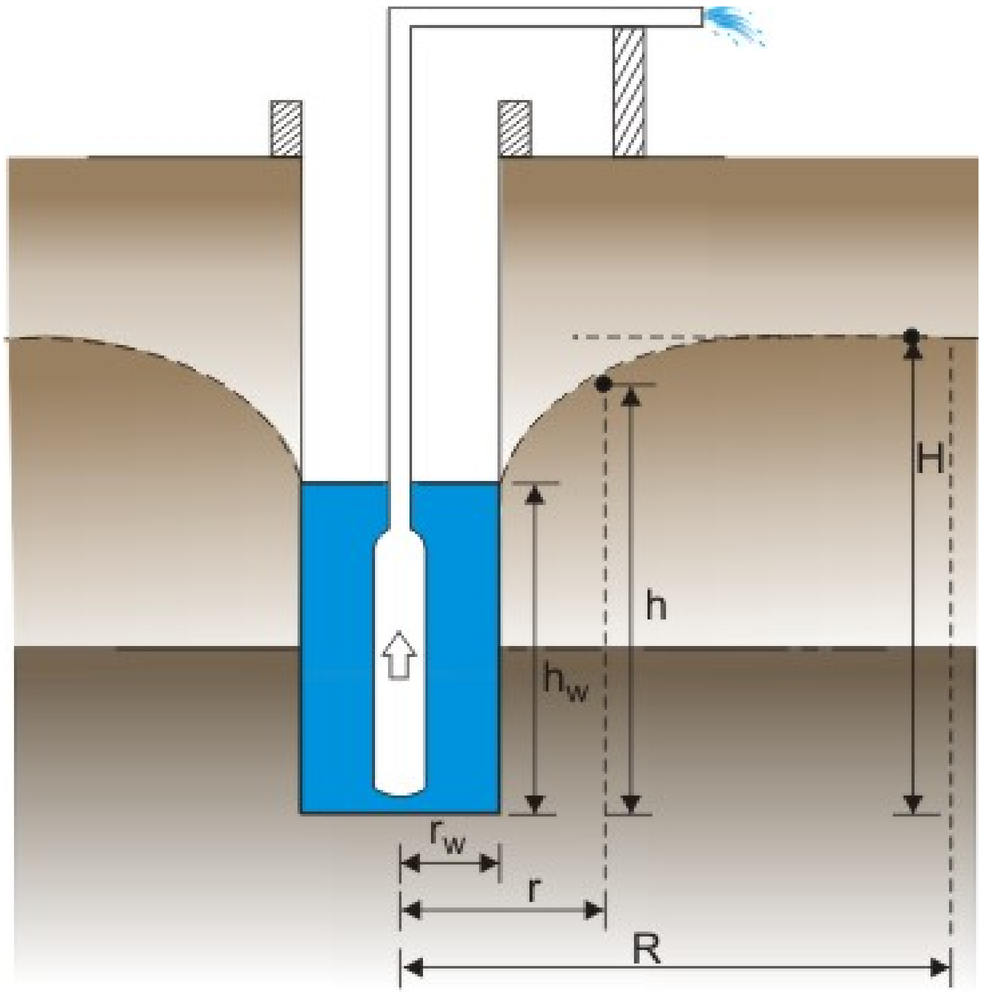

FIG 6. Definition of terms

The well is assumed to have a redius r_w and the radius of influence is thought to be R where the potentiometric surface is nearly equal to the original undisturbed value H, measured from a datum. At the well, the depth of water is designated by $\boldsymbol{h_w}$**,** which is also measured from a common datum. In general, at a certain radius r measured from the center of the well, the potentiometric surface stands at a height 'h' measured above the datum. The yield from the well Q may be expressed in terms of Darcy's law as,

$$Q = K\ i\ \mathrm{A} \tag{1}$$

Where ***K*** is the coefficient of permeability of the formation, ***i*** is the hydraulic gradient that is, the slope of the potentiometric surface at the well bound and **A** is the surface area of the well through which the flow is converging into the well from the aquifer. Thus,

$$Q = K\ \left.\frac{dh}{dr}\right|_{r=r_w} \left(2\pi\, r_w\, b\right) \tag{2}$$

In the above equation, ***b*** is the Thickness of the aquifer.

Naturally, the same amount of water also travels through the aquifer at a radial distance *r* from the center of the well. Thus, yield would also be

$$Q = K\ \frac{dh}{dr}\left(2\pi\, r\ \ b\right) \tag{3}$$

The above expression is true if the aquifer thickness ***b*** is assumed to be constant throughout. The above equations give us a value of the yield, *Q*, of the well but for that a measure of the gradient of the potentiometric surface is essential. This may be done by inserting a piezometer penetrating into the aquifer and noting the water level there (Figure 7).

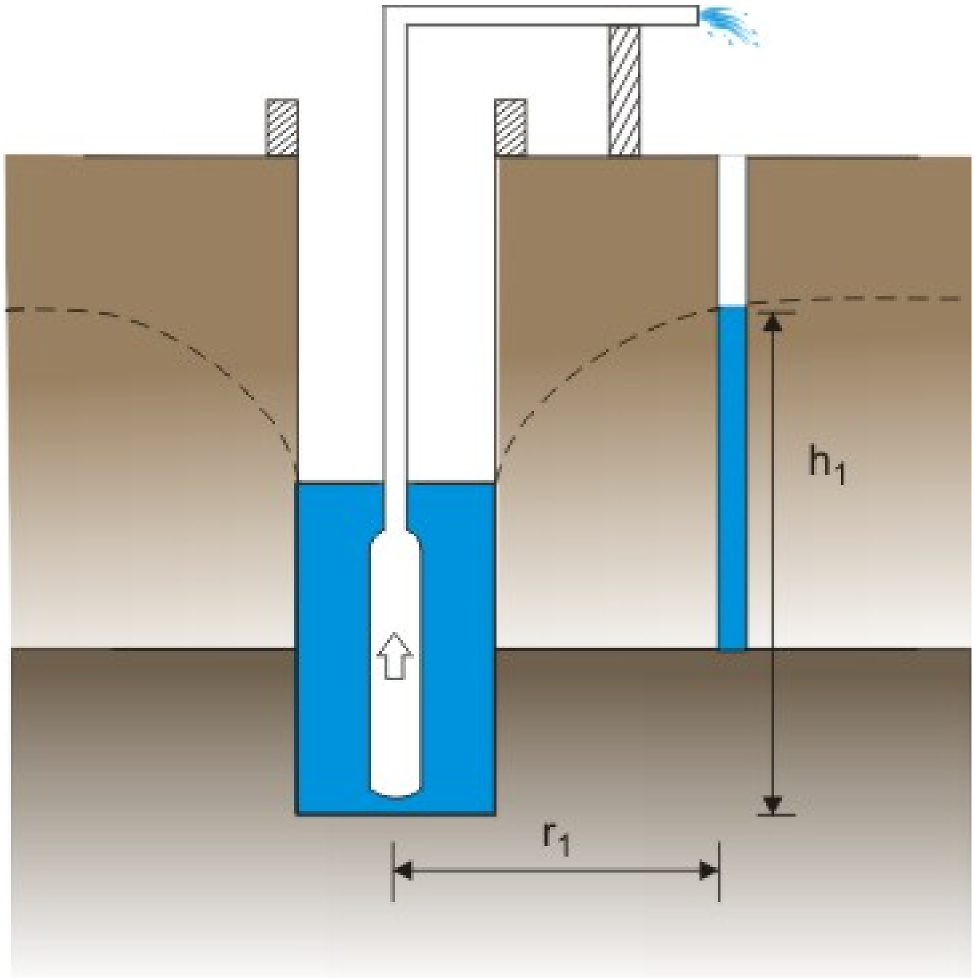

FIGURE .7 WATER VISE IN PIEZOMETER

Integrating (3) between the limits of r_w and r_1, one obtains the following expressions:

$$h_1 - h_w = \frac{Q}{2\pi k b} \ln \frac{r_1}{r_w} \qquad (4)$$

$$h_1 - h_w = \frac{2.3Q}{2\pi T} \ln \frac{r_1}{r_w} \qquad (5)$$

Where $T = Kb$ denotes the transmissibility of the aquifer.

This equation is known as equilibrium equation and can be used to determine variation of the potentiometric head radially outward from the well. The drawdown S at a radial distance r from the well (Figure 8) is given by

$$S = H_1 - h_1 = \frac{2.3Q}{2\pi T} \ln \frac{R}{r_1} \qquad (6)$$

Where ***H*** is the undisturbed initial potentimetric surface and *R* is the radius of influence. If the drawdown ***S*** at distance r from the well known it is possible to work out ***T*** or ***K*** as

$$K = \frac{2.3Q}{2\pi S_1} \ln \frac{R}{r_1} \tag{7}$$

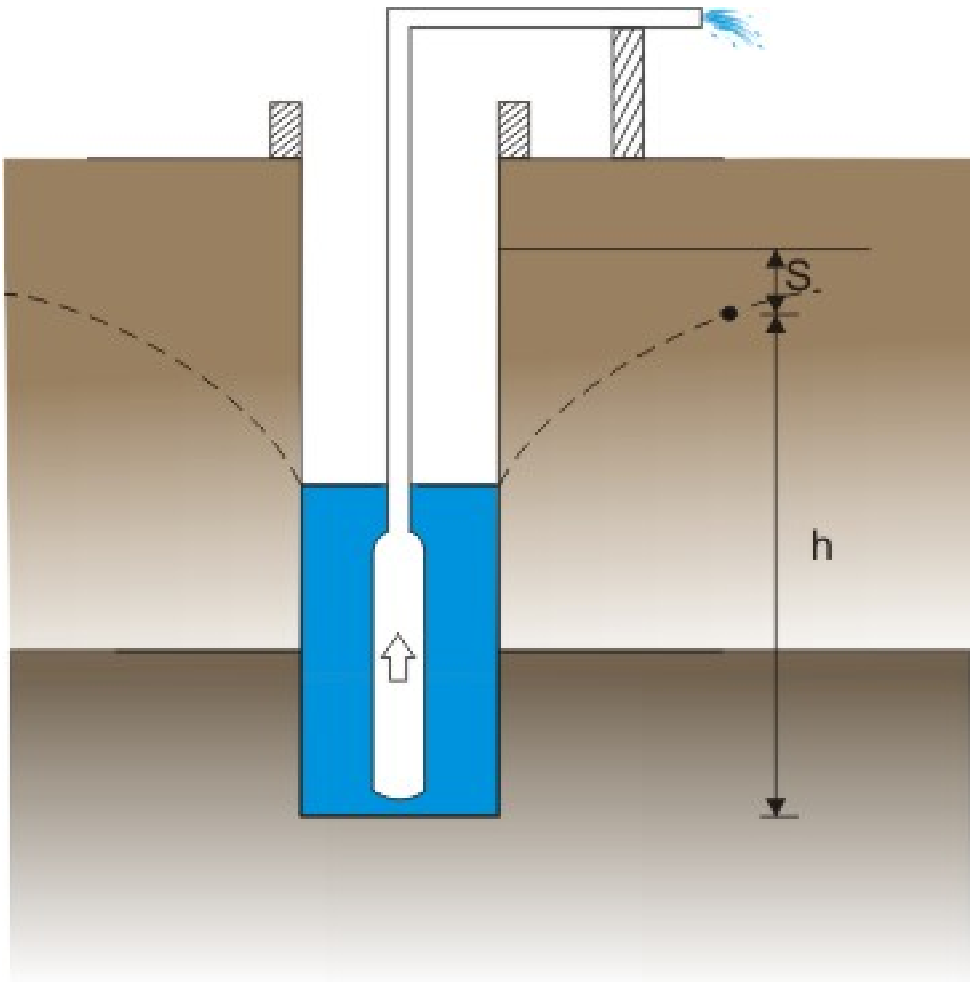

FIGURE .8 DEFINITION OF DRAWDOWN : S

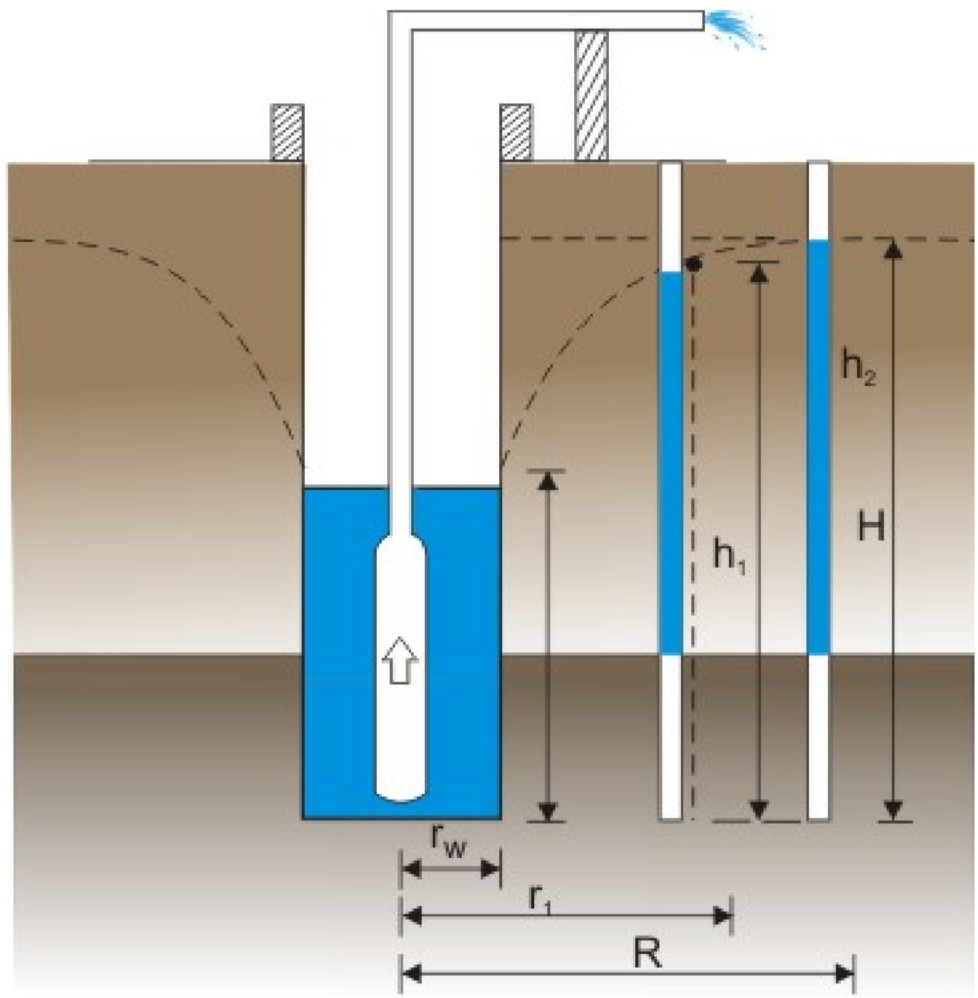

FIGURE . 9 DEFINITION OF TERMS

In case two piezometers are inserted near a well (Figure 9) and the piezometric head at these two places are given as $\boldsymbol{h_1}$ and $\boldsymbol{h_2}$, then the following expression is arrived at:

$$K = \frac{2.3Q}{2\pi b(h_2 - h_1)} \ln \frac{r_2}{r_1} \tag{8}$$

This method of determining the permeability of an aquifer is known as Thiems method. Details about the method may be had from standard text books on ground water as the following:

Raghunath, H M (1998) ***Ground Water*****,** Second Edition, New Age International Publishers.

2.7.3 Steady Flow to a Well: Unconfined Aquifer

For the case of a pumped well located in an unconfined aquifer (Figure 10) the steady state discharge conditions are similar to that of confined aquifer.

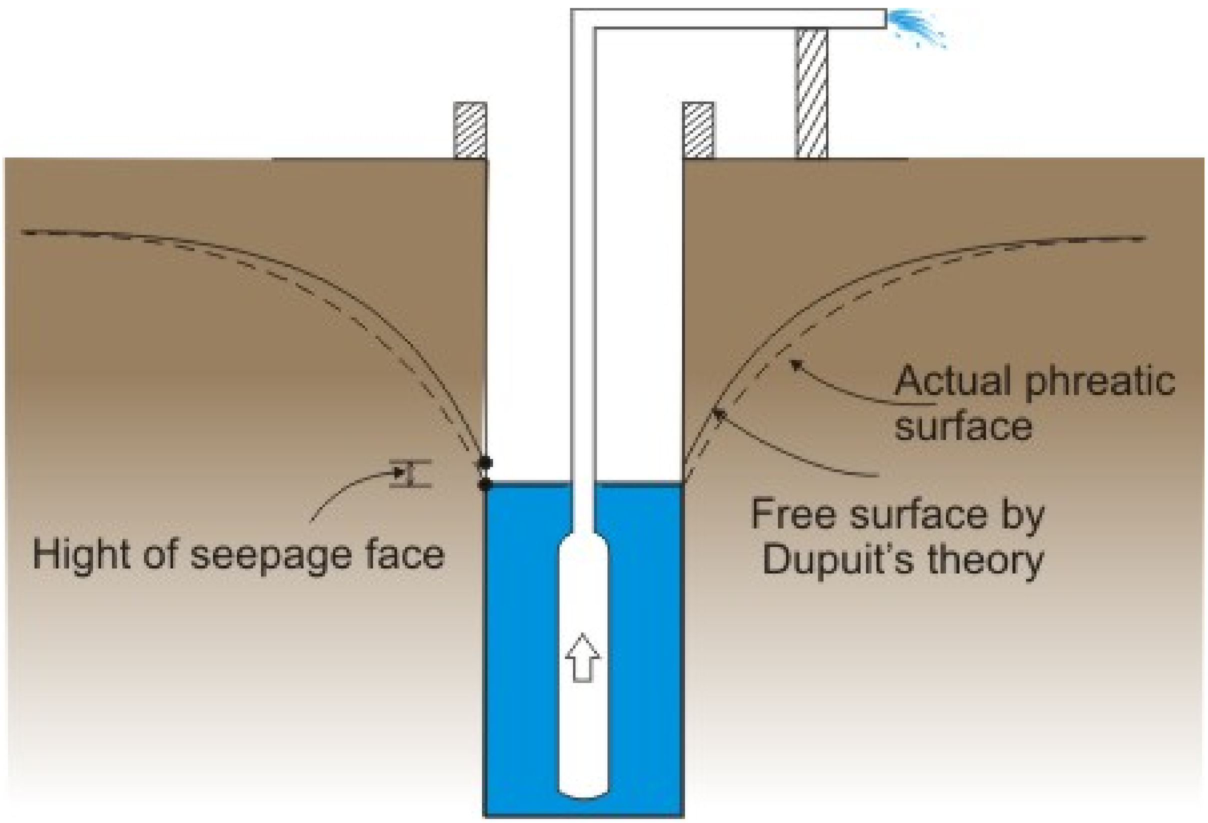

FIGURE .10 ASSUMPTION FOR DUPUIT'S THEORY

The flow at radial distance ***r*** from the well is given by the following equation under the simplifying assumptions made by Dupuit.

$$Q = 2\pi \; r \; K \; h_1 \left. \frac{dh}{dr} \right|_{r = r_1} \tag{9}$$

Where ***h*** denotes the height of the water take at a distance ***r*** above a datum, which may be the bedrock. Integrating between the limits of r_w and r_1

$$h_1{}^2 - h_w{}^2 = \frac{2.3Q}{\pi K} \ln \frac{r_1}{r_w} \tag{10}$$

By knowing the values of the water table at two places located at distances r_1 and r_2 from the centre of the well with corresponding heads h_1 and h_2 the value of the coefficient of permeability K can be worked out from the equation.

The water table head at any radial distance r can also be expressed in terms of H, the head at undisturbed initial water table before pumping as:

$$H^2 - h^2 = \frac{2.3Q}{\pi K} \ln \frac{R}{r} \qquad (11)$$

In the above expression, R is the radius of influence of the radial distances where the water table head is nearly equal to H.

Since (9) was derived with Dupuit's assumption (refer to Lesson 2.6), the actual free surface will be slightly higher than the predicted free surface. This is because the gradient of the cone of depression is larger towards the well where the curvature of streamlines is most marked. The free surface of water table will actually meet the periphery of the well at some height above the water level in the well as shown in Figure 10.

2.7.4 Unsteady flow to a well: Confined aquifer

When a well starts pumping out water at constant rate, the potentimetric surface gradually gets lowered. The unsteady state representation of the potential head in such a case is given by the following expression,

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (12)$$

Where h is the potential head at a distance from the well at a time t; S is the Storativity and T is the Transmissivity. The boundary and initial conditions are defined as follows:

- The potential head is equal to H, the undisturbed potential head at $r \geq R$ and for all times, that is for $t \geq 0$
- At the well face, that is at $r = r_w$, the flux (or water getting discharged), Q, is related to the gradient of the potentiometric surface as,

$$r\frac{\partial h}{\partial r}\bigg|_{r=r_w} = -\frac{Q}{2\pi T} \qquad (13)$$

- The initial condition that is at time $t = 0$, the following condition holds:

$$h\big|_{at\ any\ r} = H \qquad (14)$$

A solution of (13), based on the boundary and initial conditions, was given by Theis as in the following equation. Interested readers may refer to text books on ground water for further details.

$$H - h = -\frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + ...\right] \qquad (15)$$

The unsteady state representation of the piezometric head, when the piezometric surface gradually gets lowered during of the well is given as:

$$u = \frac{r^2 s}{4T t} \qquad (16)$$

In equation (15), ***H–h*** is the drawdown at any radial distance ***r***, measured from the centre of the well. The infinite series term in the equation is generally designated as ***W(u)***, and in textbooks on well hydraulics as Raghunath (1998), these are tabulated for ease of calculation. However, with the help of calculators, it is easy to evaluate the first three terms and for practical calculations, only the first three or four terms may be considered. If only the first two terms are taken, then the expression simplifies to:

$$H\text{-}\ h = \frac{Q}{4\pi T}\left[-0.5772 - \ln u\right] \qquad (17)$$

$$= \frac{Q}{4\pi T}\left[\ln \frac{2.25 T t}{r^2 S}\right] \qquad (18)$$

$$= -\frac{0.183 Q}{T}\left[\ln \frac{2.25 T t}{r^2 S}\right] \qquad (19)$$

For values of ***u*** less then 0.05, the value of ***H-h*** evaluated by (19) is practically the same as that obtained by applying (15).

2.7.5 Unsteady flow to a well: Unconfined aquifer

As with confined aquifers, the decline in pressure in the aquifer yields water because of the elastic storage of the aquifer Storativity (***Ss***). The declining water table also yields water as it drains under gravity from the sediments. This is termed as specific yield (s_y). The flow equation has been solved for radial flow in compressible unconfined aquifers under a number of different conditions and by use of a variety of mathematical methods. It is not in the scope of the present text to discuss these methods. The interested reader may refer to textbooks on well hydraulics, for examples “Ground Water” by H.M. Raghunath, New Age International (P) Ltd, Publishers.

2.7.6 Determining properties of confined aquifer

The hydraulic properties of a confined aquifer are often required to be known and the equations discussed in Section 2.7.2 or 2.7.4 can be used if measurements of water levels at known value of the discharge rate.

If the observations correspond to equilibrium conditions, then two observation wells, data may be used along with equation (6), to yield

$$T = \frac{Q \log\left(r_2 / r_1 \right)}{2.73\left(h_2 - h_1\right)} \qquad (20)$$

Where ***T*** is the Transmissivity of the confined aquifer and $\boldsymbol{h_1}$ and $\boldsymbol{h_2}$ are the depth of piezometric heads at two observation wells located at radial distance $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ respectively from the pumping well centre.

For non-equilibrium conditions, equation (19) would yield:

$$T = \frac{0.183 Q}{\left(S_2 - S_1\right)} \log\left(\frac{t_2}{t_1}\right) \qquad (21)$$

Where $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ are the draw downs in an observation well at a radial distance r from the pumping well – centre at times $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$.

Having known ***T***, the Storativity ***S*** of the aquifer may be determined using (13).

2.7.7 Design of wells for water supply

A well is an intake structure dug on the ground to draw water from the reservoirs of water stored within. The water from the well could be used to meet domestic, agricultural, industrial, or other uses. The structure may be an open dug well, or as is common these days, may be tube-wells. The well may be shallow, tapping an unconfined reservoir or could be deep, penetrating further inside the ground to tap a confined aquifer located within aquicludes. In this lesson, we shall discuss the design of tube wells, a typical installation of which is given in Figure 11.

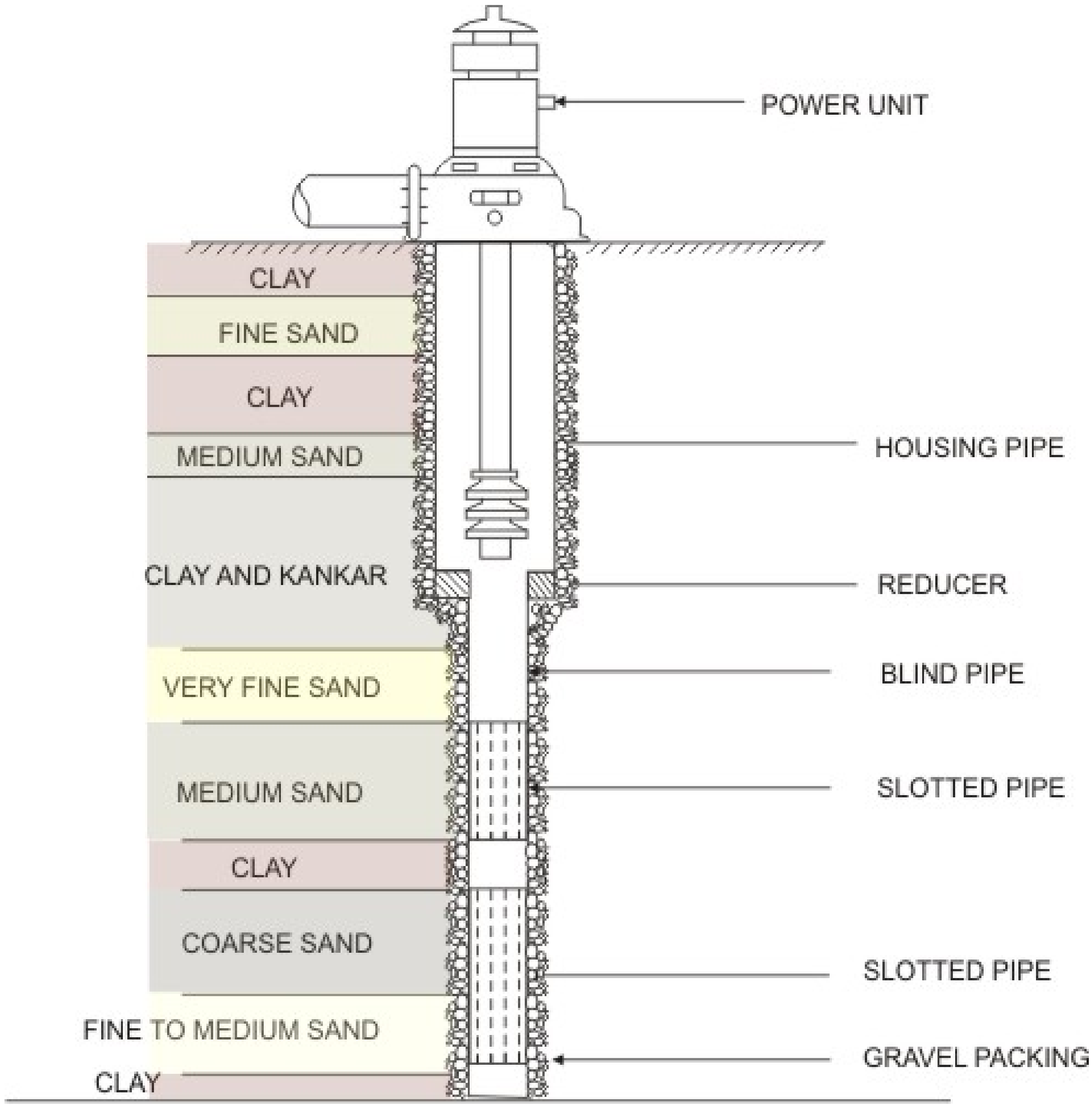

FIGURE . 11 TYPICAL INSTALLATION OF TUBE WELL

Design of a well involves selecting appropriate dimensions of various components and choosing proper materials to be used for its construction. A good design of tube well should aim at efficient utilisation of the aquifer, which it is supposed to tap, have a long and useful life, should have a low initial cost, and low mantenace and operation cost. The parameters that need to be designed for a well include the following:

- Well diameter
  The diameter of the well must be chosen to give the desired percentage of open area in the screen (15 to 18 percent) so that the entrance velocities near the screen do no exceed 3 to 6 cm/s so as to reduce the well losses and hence, the draw down. The velocity should be reasonably low as indicated, such that the five particles within the sand should not migrate towards the well strainer slots.

- Well depth

- Selection of strata to be tapped
  The samples during drilling are collected from various depths and a bore log is prepared. This log describes the soil material type, size distribution, uniformity coefficient etc. for the material available at different depths.

- Well screen design
  This includes fixing the following parameters for a well:
  - Well screen length
  - Well-screen slot size
  - Well-screen diameter
  - Well-screen material

In case of unconfined aquifers, where too thick and homogeneous aquifer is met, it is desirable to provide screen in the lower one third thickness. In case of confined aquifers where thick and nearly homogeneous aquifer is met, about 80 to 90 percent of the depth at the centre of the aquifer is advised to be screened. Where too thick and homogeneous aquifers are encountered it is common practice to place screen opposite the more permeable beds leaving about 0.3m depth both at the top and bottom of the aquifer, so that finer material in the transition zone does not move into the well.

The size of the well screen slots depends upon the gradation, and size of the formation material, so that there is no migration of fines near the slots. In case of naturally developed wells the slot size is taken as around 40 to 70 percent of the size of the formation material. If the slot size selected on this basis comes to less than 0.75 mm, then an artificial ground pack is used. An artificial gravel pack is required when the aquifer material is homogeneous with a uniformity coefficient less than 3 and effective grain size less than 0.25 mm.

The screen diameter is determined so that the entrance velocity near the well screen does not exceed 3 to 6 cm/sec.

The screen material should be resistant to incrustation and corrosion and should have the strength to withstand the weight of the well pipe. The selection of the screen material also depends on the quality of ground water, diameter and depth of the well and type of strata encountered.

2.7.8 Installation of tube wells

The entire process of installation of tube wells include drilling of a hole, installing the screen and housing pipes, gravel packing and development of the well to insure sand free water. Depending on the size of the tubewell, depth and formation to be drilled, available facility and technical know-how, different methods are used for the construction of tubewells. Two methods that are commonly used are explained below.

- ***Cable-tool percussion drilling***
  A rig consists of a mast, lines of hoist for operating the drilling tool and a sand pump (Figure 12).

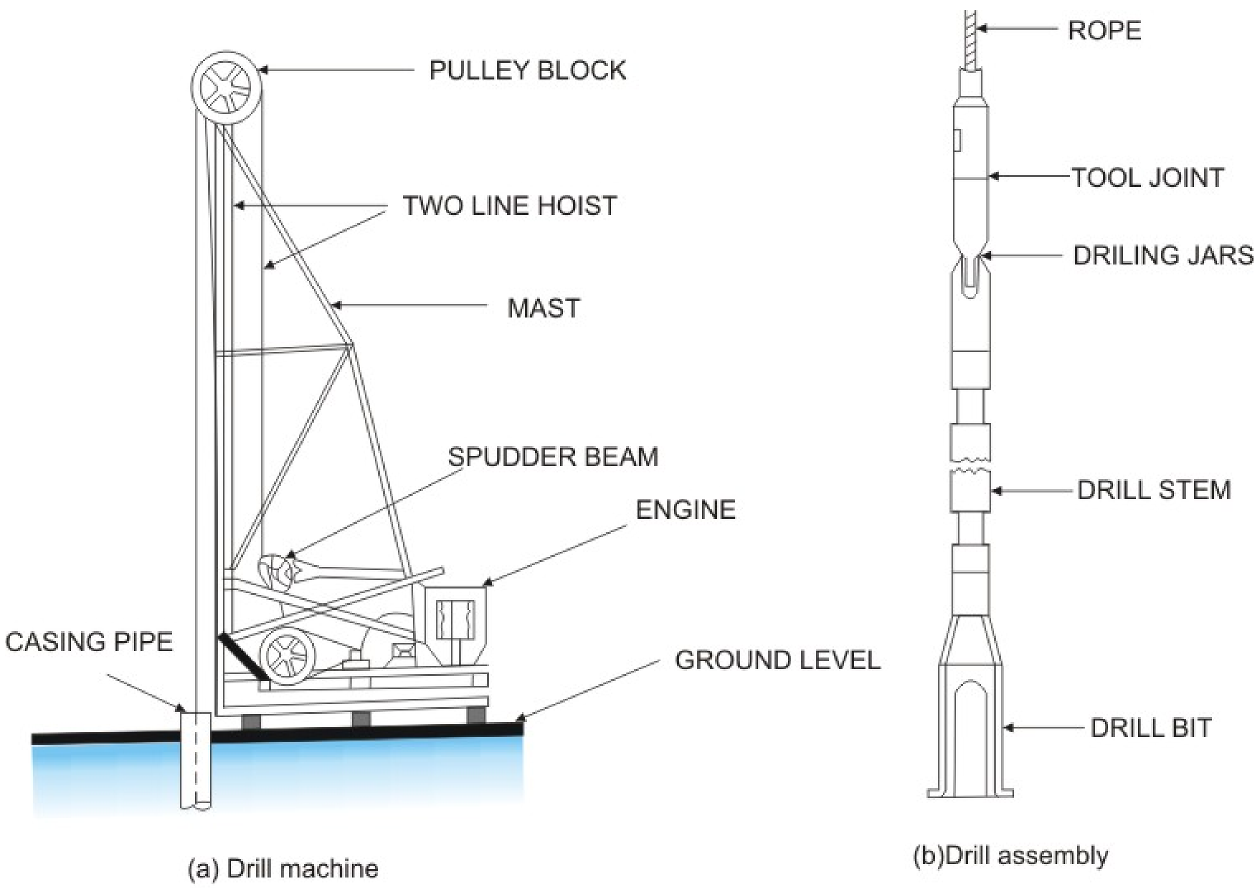

FIGURE .12 CABLE TOOL PERCUSSION DRILLING

The cutting tool is suspended from a cable and the drilling is accomplished by up and down movement (percussion) of the tool. A full string of drilling tool consists of four components:

- Drill bit
- Drill stem
- Drilling jars
- Rope socket

The drill bit is used to loosen the formation material and its reciprocating action breaks it down to smaller particles or muck. Water injected from the top converts the muck into slurry. For this purpose water is added as long as drilling continues in dry formations. The slurry flows up due to the pressure of water. The drill stem fixed just above the bit provides additional tools in order to maintain a straight line. The drilling jars consist of a pair of linked steel bars and can be moved in a vertical direction relative to each other. The rope socket connects the string of tools to the cable.

- ***Rotary Drilling method***

There are two main types of rotary drilling methods:

- Direct rotary methods, and
- Reverse rotary method

In either case, a rotating bit is used as a drilling bit. The major difference is in the direction of the flowing fluid (Figure 13).

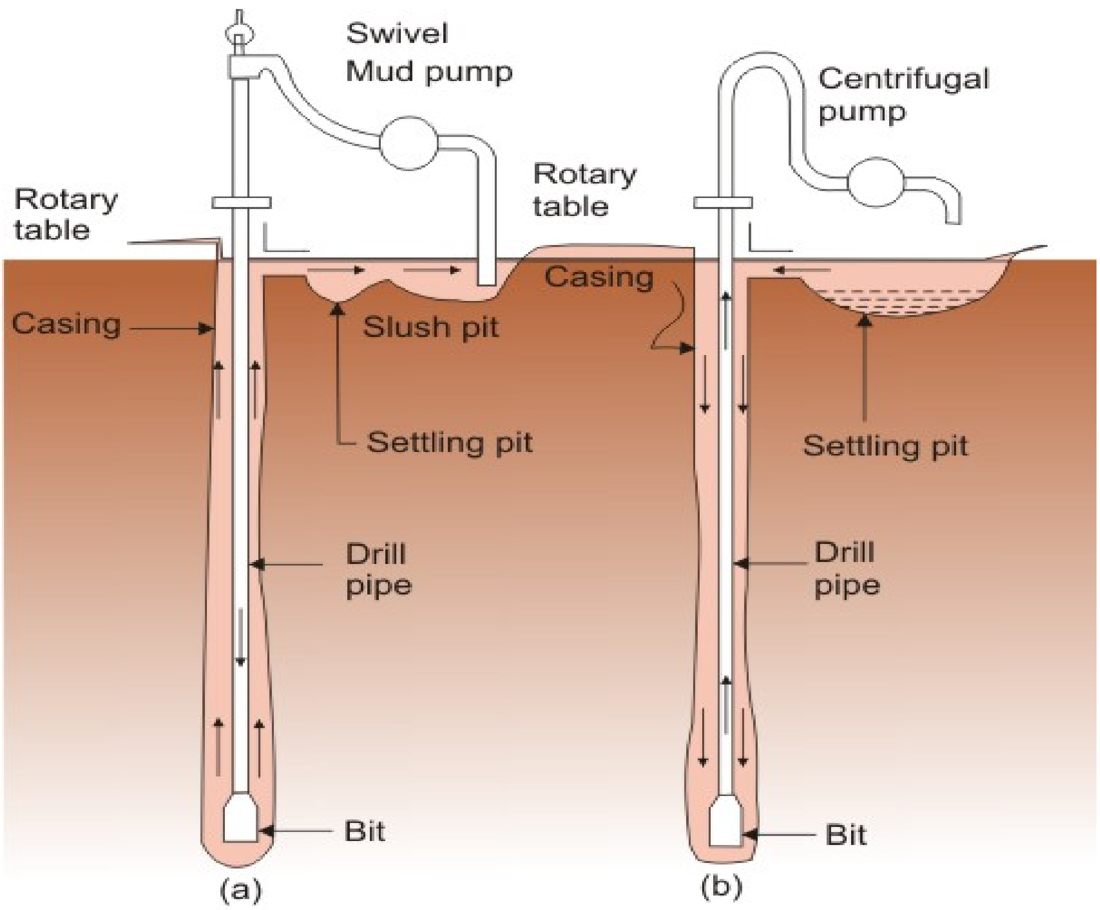

FIGURE . 13 ROTARY DRILLING (a) Hydraulic rotary (b) Reverse rotary

The rotary drilling method, also sometimes called the hydraulic rotary method of drilling, uses continuously circulating pumped fluid. The power to the drill bit is delivered to the bit by a rotating hallow steel pipe or drill pipe. The drilling fluid or bentonite slurry is pumped down through the drill pipe and out through a nozzle in the drill bit. The mud then rises to the surface through the hole and also removes the drilled formation material or muck. At the surface the fluid is led to a setting pit and then to a storage pit from where it is pumped back into the hole. Water and clay are added to the storage in to maintain quantity and consistency.

Well screens

For installation of well screens, different methods are used depending upon the design of the well, the type of well, locally available facility and the type of problems encountered in drilling operation. The Pull-back method is generally used with the cable-tool percussion method of well drilling. After the casing pipe has reached to the depth where the bottom of the screen is to be located, the sand that might have flowed into the pipe is removed. The well assembly consisting of screen and blind pipe lengths is lowered into the well. A heavy plate bail handle is provided at the bottom of the screen. The lowering of the assembly may be accomplished by suspending it by the bail handle using a flat hook attached to the sand line to engage the bail. After lowering the complete well screen assembly inside the casing pipe, the casing rip is pulled back.

For rotary drilled wells generally the Open-Hole method of screen installation used, though the Pull–Back method can also be used in this case too. In the open-hole method, after drilling the hole below the well caring, the drill stem is withdrawn and a telescope–size screen is lowered into the hole by any suitable method. The depth of the hole should be checked such that when the screen rests on the bottom of the hole, the lead packer should remain inside the lower end of the casing.

Gravel packing

Well can either manually ground packed or artificially ground packed. Natural ground packed condition is created by removing the fine sand from the formation either by pumping or by surging. An artificially gravel packed well has a envelop of specially grand sand or gravel placed around the well screen. Ground pack is designed on the basis of sieve analysis of the aquifer materials obtained during drilling. Aquifer consisting of coarse materials of less uniform sizes may not require any gravel pack.

Well Development

This process is used to remove sand, silt and other fine materials from a zone immediately surrounding the well screen. This is done by flow reversal through the screen openings so as to rearrange the formation particles in a naturally developed well and form a graded filter with materials of increasing porosity and permeability towards the well in an artificially gravel packed well, so that ultimately the well will yield clear sand free water.