

GROUND WATER ENGINEERING

CV0612

GROUND WATER RECHARGE

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MANAGEMENT OF GROUNDWATER RESOURCES

Groundwater management aims to achieve certain strategies for sustainable use of the resources. Some of the objectives of the groundwater management models are:

- z **Maximization of total withdrawal** from an aquifer.
- z **Minimization of cost** of per unit volume of water supplied to the consumers.
- z Maximization of net **benefit** of a project related to the supply of water for municipal, industrial, agricultural, etc. purposes.
- z Minimization of total consumption of energy of project related to the **extraction and distribution of groundwater**.
- z Minimization of an error function obtained from the sum of the absolute difference between **actual and predicted values of certain water level**.

CONSTRAINTS IN GROUNDWATER MANAGEMENT

Some of the commonly applicable constraints in groundwater management models are:

- z Water level at any location in an aquifer should not go below certain value. This constraint will put restriction on the depletion of water table due to pumping of water from an aquifer.
- z Water level at any location in an aquifer should not rise above certain level. This is required to avoid water logging of an area and also to dewater an area under construction.
- z Limits on the maximum and minimum withdrawal of water from an aquifer
- z Spring discharge should not go below certain specified value.
- z Base flow of a stream or a river should not go below certain minimum value.
- z Quality of pumped water should not deteriorate below certain specific value.
- z Limit on land subsidence.

ARTIFICIAL RECHARGE

- z Artificial recharge is a process by which the groundwater reservoir is augmented artificially.
- z The rapid urbanization and deforestation have considerably reduced the groundwater recharge in many parts of the world.
- z The reduction in groundwater recharge and over exploitation of groundwater due to increasing demands, the groundwater table has been depleted in many parts of the world. For example, the groundwater table in some parts of Delhi has been depleted by 20 to 30 meters in a span of 60 years.
- z there is a need to increase the groundwater recharge by some artificial means

TECHNIQUES OF GROUNDWATER RECHARGE

- z The artificial techniques use for groundwater recharge can be divided in two groups, *i.e.* direct method and indirect method.
- z The main objective of the surface method is to enhance groundwater infiltration by providing more residence time with the help of structural and nonstructural measures.

Direct Methods

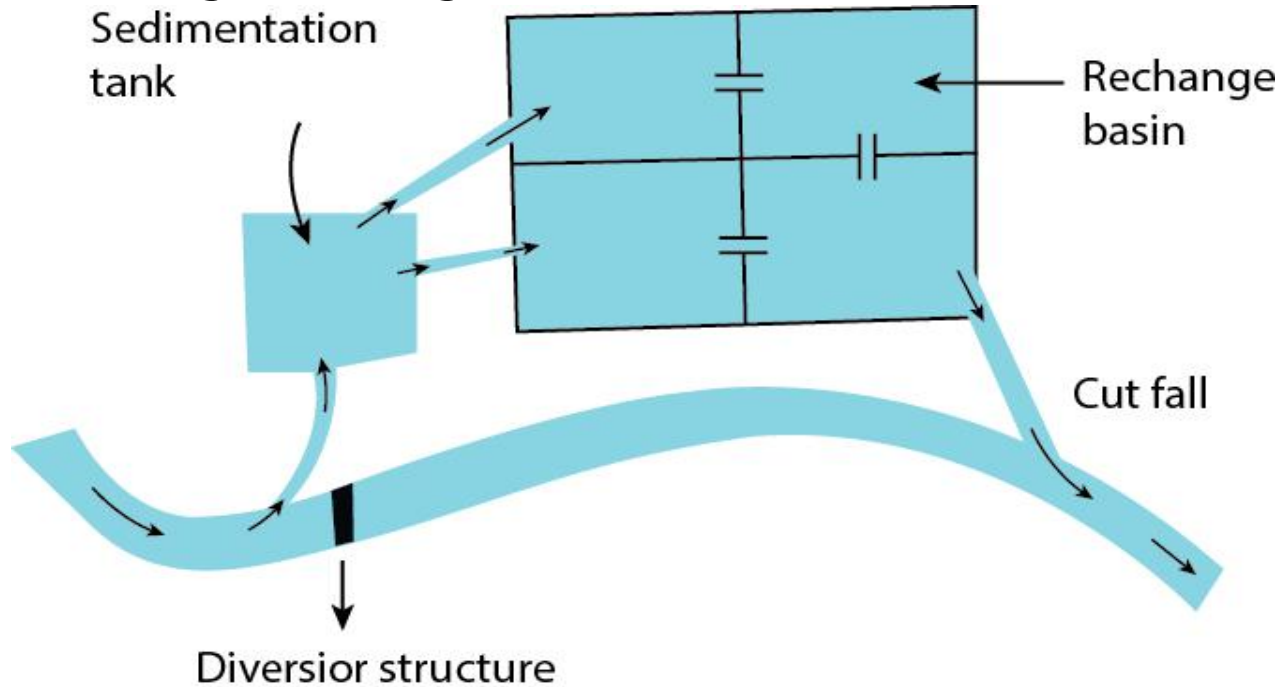
Surface method

1. Percolation tank

- z In this method, series of earthen dams are constructed on suitable sites for storing of adequate quantity of surface water.
- z The tank area should be selected in such a way that significant amount of water infiltrates through the bed of the tank and reaches the groundwater table.
- z This method is very effective in alluvial area as well as in areas with hard rock.
- z This method is very useful in providing continuous recharge

2. Flooding

- z This method is suitable for relatively flat region where water can be spread as a thin layer.
- z Water is distributed over the region using a distribution system.
- z This method can achieve higher rate of infiltration in a region having thin vegetation cover or sand soil cover.



3. Stream augmentation

- z In this method, seepage from natural stream or river is artificially increased by putting some **series of check dams** across the river or stream.
- z The placing of check dams spread the water in a larger area which eventually increases groundwater recharge.
- z The sites for the check dams should be selected in such a way that sufficient thickness of permeable bed is available for quick recharging the stored water.

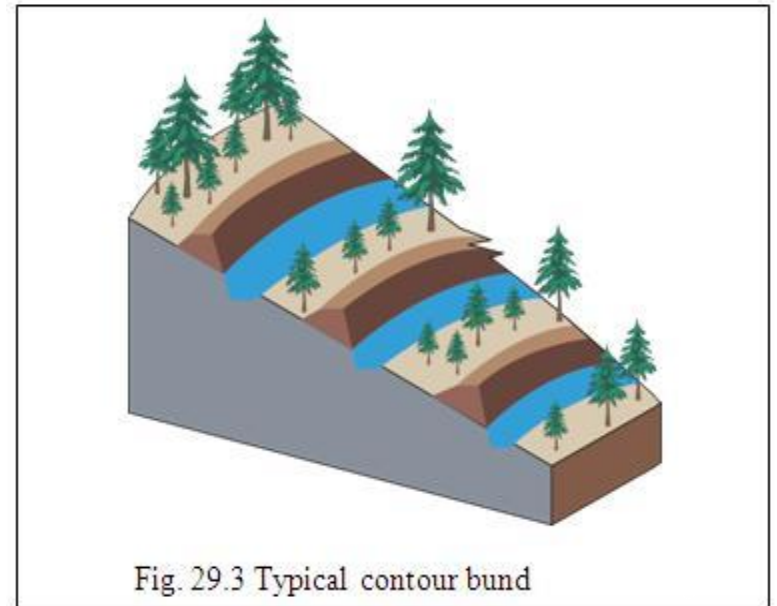
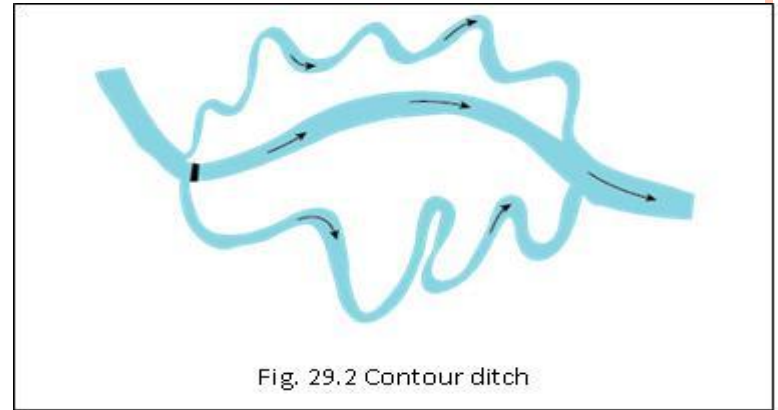
4. Ditch and furrow system

- z This method is used for uneven terrain.
- z In this technique, a system of closely spaced flat bottom ditch or furrow is used to carry the water from the source.
- z This system provides more opportunity to percolate the water into the ground.

- The spacing of the ditch depends on the permeability of the soil.
- For less permeable soil, more densely spaced ditch or furrow should be provided.

5. Contour bund

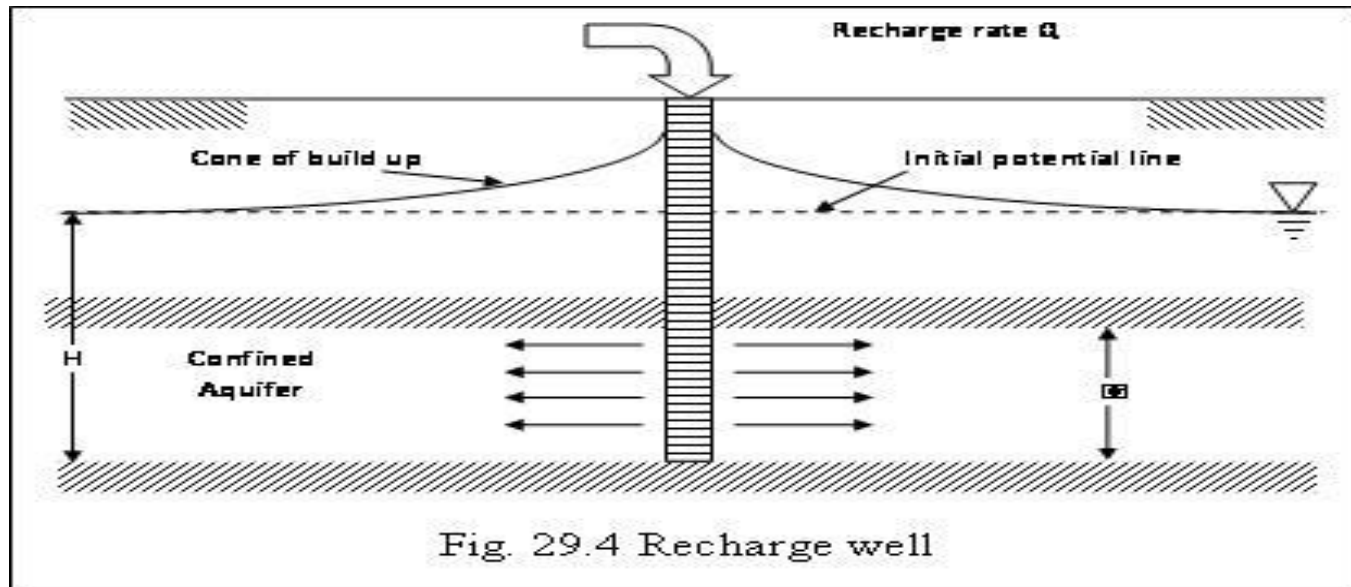
- Contour bund is a small embankment constructed along the contour in hilly region to retain the surface runoff for longer time.
- This scheme is adopted for low rainfall area where internal subsurface drainage is good.



z **Subsurface method**

1. Recharge well

- z Recharge wells are used to recharge water directly to the aquifer.
- z Recharge wells are similar to pumping wells.
- z This method is suitable to recharge single wells or multiple wells.
- z This method is costlier than the other method as wells are required to be bored.



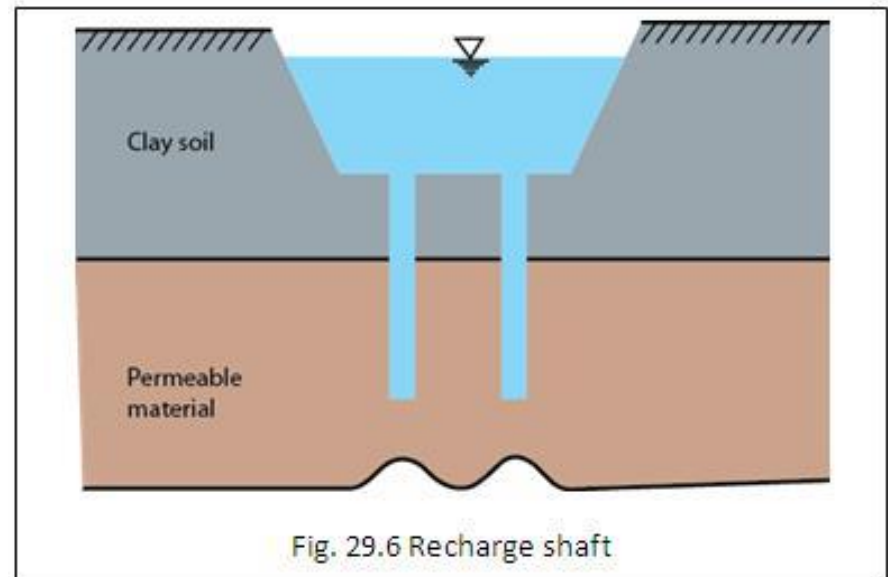
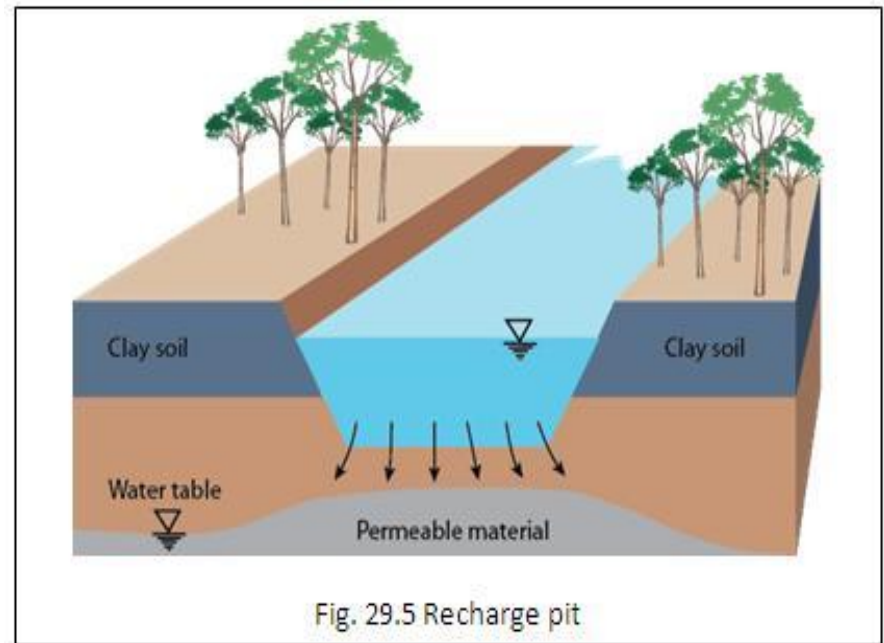
2. Dug well

- z Dug wells can also be used to artificially recharge the groundwater.
- z Generally, water level of dug wells depletes during the non monsoon period.
- z Sometime the dug wells even dried up in the non-monsoon period.
- z These dug wells can be used for recharging groundwater.
- z The water from various sources can be collected through a distribution system and can be discharged at the dug wells.

3. Pits and shafts

- z Recharge pit of variable dimensions are used to recharge water to unconfined aquifer.
- z Most of the time, especially in case of agricultural field, a layer of less permeable soil exist.
- z Due to the existence of the less permeable

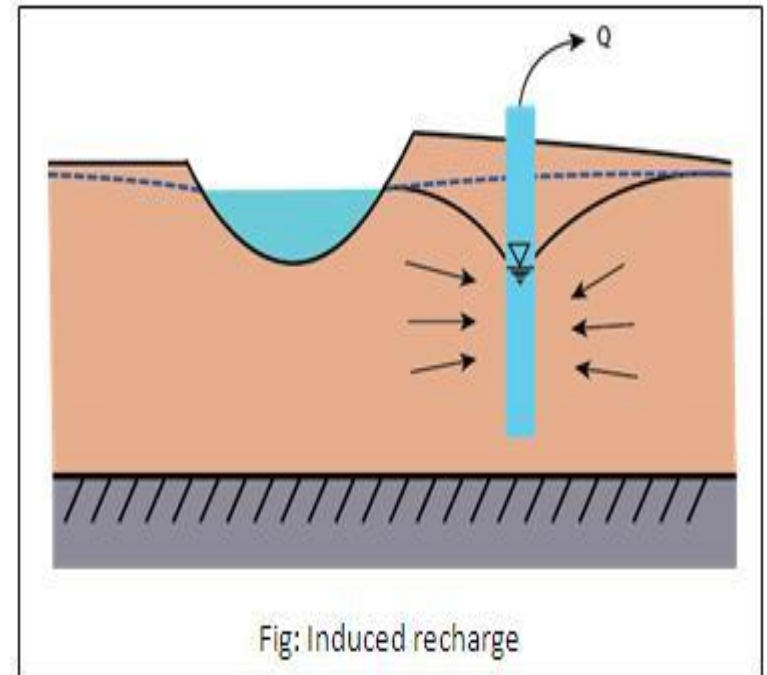
- permeable strata, the surface flooding methods of recharge do not show satisfactory performance.
- For such type of cases, recharge pit can be excavated which are sufficiently deep to penetrate the less permeable strata.
- recharge shaft is similar to the recharge pits, but the cross sectional size of the recharge shaft is much lesser than the recharge pits.
- recharge shafts are also used to recharge water to unconfined aquifer whose water table is deep below the land surface and a poorly impermeable strata exist at the surface level.



Indirect method

1. Induced recharge

- It is an indirect method of artificial recharge.
- In this method water is pumped from the aquifer hydraulically connected to the surface water sources like stream, river or lake.
- Due to pumping, a reverse gradient is formed and water from the surface water source enters into the aquifer and thus the aquifer is recharged .



- This method is good, especially when quality of the surface water is poor.
- The filtration of surface water through soil strata removes the impurities of the water.
- Thus the quality of the water receives in the wells is much better than the surface water.

2. Aquifer modification method

- z This is also an indirect method of artificial recharge. In this method, some techniques are used to change the aquifer characteristic so that aquifer can store more water and also can transmit more water.
- z The most commonly used techniques are, bore blasting method, hydro-fracturing method, jacket well techniques, fracture seal cementation and pressure injection grouting, etc.

2.1. Bore blasting method

- z This method is used to increase the fracture porosity of an aquifer.
- z Shallow bore wells are drilled in the area where fracture porosity of the aquifer is planned to increase.
- z These bore holes are blasted with the help of explosive which creates fracture porosity in the aquifer.

2.2. Hydro-fracturing method

- z Hydro-fracturing is used to improve the yield of a bore well.
- z In this technique, water is injected at a very high pressure to widening the existing fracture of the rock.
- z The high pressure injection of water also helps in removing of clogging, creates interconnection between the fractures, and extends the existing length of the old fracture.
- z The high pressure injection also creates new fracture in the rock strata.
- z As a result of these, the water storing and transmitting capacity of the strata increases.

2.3. Jacket well techniques

- z Jacket well technique is used to increase the yield of a dug well.
- z In this method, the effective diameter of the well is increased by drilling small diameter bores around the well in a circular pattern.

2.4. Fracture seal cementation and pressure injection grouting

- z This technique is used to control the outflow from an aquifer.
- z Cement slurry is injected into the aquifer using mechanical means or manually near to the aquifer outlet like spring, etc.
- z The injection of cement slurry helps in reducing the fracture porosity of the aquifer near the outlet which will eventually reduce the outflow from the aquifer.

Thank you

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UNIT - IV

**TUBE WELLS AND THEIR
DESIGN**

2. Tube wells

- **Tube wells** consists essentially of a hole bored in to the ground for tapping ground water from deep pervious zones.
- Compared to open wells, tube wells have small diameter(usually 8cm - 60cm) and deep/larger depth (more than 30m).
- Yield from standard tube well 40-45 l/s.
- Shallow tube wells : 30-60m depth, 20 L/s yield
- Deep tube wells : 60-300 m depth, yield 200 L/s

Types of Water well

Open Well

Depending on Nature of Ground Water Formation to be Tapped

Open Well in Unconsolidated Formation

Open Well in Hard Rock Formation

Unlined Well

Wells with pervious lining

Wells with impervious lining

Dug-cum-bore wells

Dug wells in hard-rock formations

Dug-cum-bore wells in hard-rock formations

Tube Well

Based on Entry of water

Screen wells

Cavity wells

Based on Method of construction

Drilled wells

Driven wells

Jetted wells

Based on Depth

Shallow wells

Deep wells

Based on Type of aquifer

Water table wells

Artesian wells

Flowing Artesian wells

ADVANTAGES AND DISADVANTAGES OF TUBE WELLS

| N o | ADVANTAGES | DISADVANTAGES |
|--------|--|--|
| 1 | Do not require much space | Requires costly & complicated drilling |
| 2 | Can be constructed quickly- not time consuming | equipment & machinery Requires skilled workers & great care to drill & |
| 3 | Fairly sustained yield of water can be obtained even in years of | complete the tube well. Installation of costly turbine or submersible |
| 4 | drought Economical when deep seated aquifers are encountered. | Possibility of missing the fractures, fissures & joints in hard rock areas resulting in many dry |
| 5 | Generally good quality of water is tapped | holes. |

Tube wells cont...

Tube wells are classified on the basis of: the entry of water into the well, the method of construction, the depth and the type of aquifer tapped.

● **Based on Entry of water**

Tube wells are classified as

- **screen wells** and
- **cavity wells**

Tube wells cont...

Screen wells

- It permit the entry of water from the surrounding aquifer
- Screens are lowered into the bore hole.
- Usually limited to shallow depths

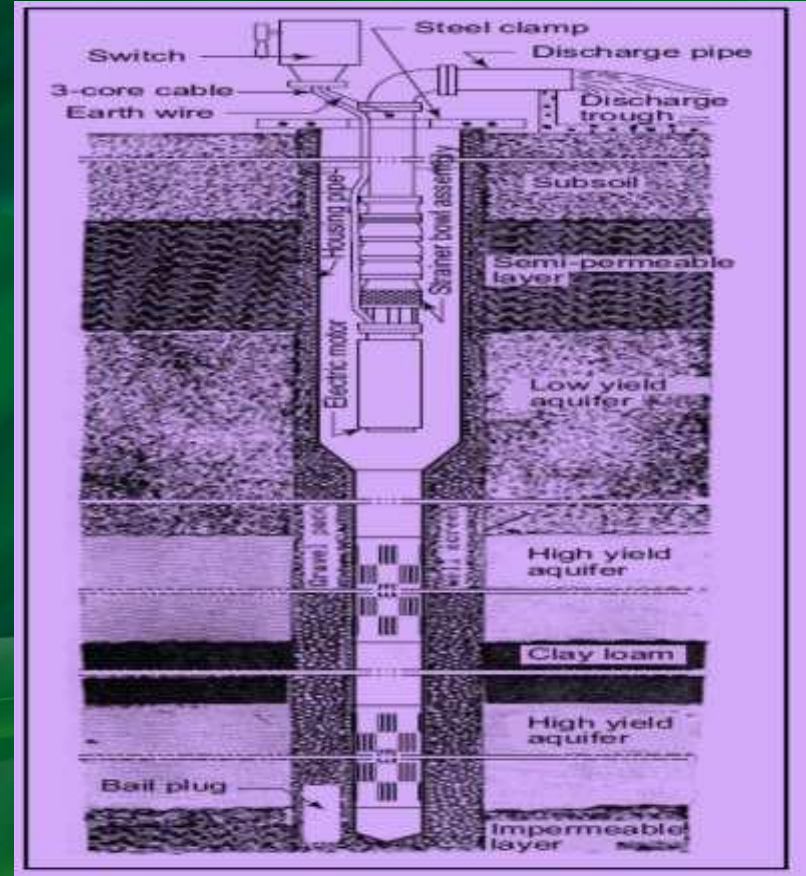
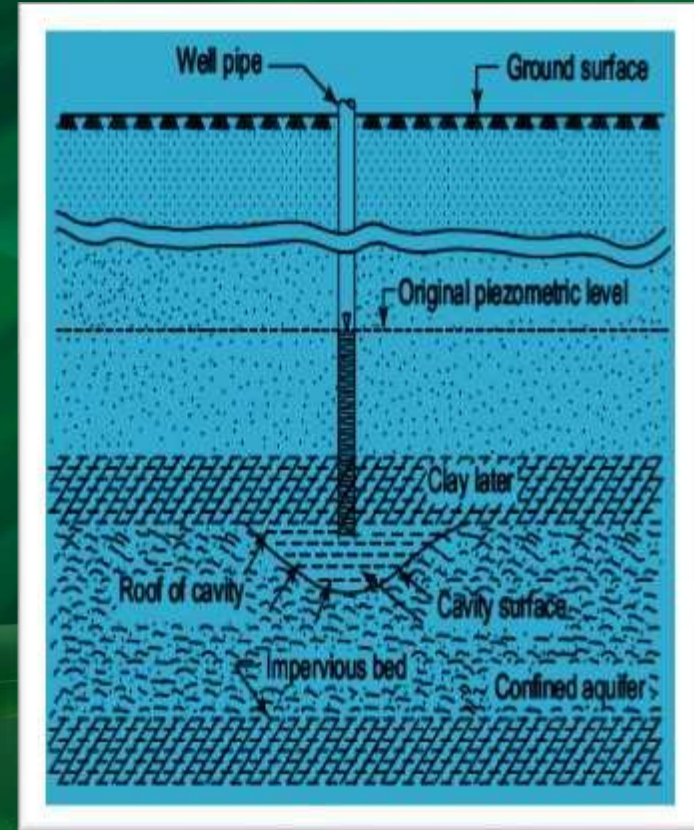


Fig-1.6 Tube wells using screens to permit the entry of water

Tube wells cont...

Cavity well

- A cavity well is a shallow tube well drilled in an alluvial formation.
- Draws water through the bottom of the well pipe.
- Cavity wells are very economical and can be adopted where the ground strata permits its construction.
- Requires strong and dependable roof



Schematic sketch of a cavity well

Based on method of construction

Grouped as: drilled wells, driven wells and jetted wells

1. Drilled tube wells

- Drilled wells are constructed by making bore holes, using different drilling methods.
- Tube well construction involves drilling the bore hole, installing the casing and well screen, and developing the well to ensure sand-free operation at maximum yield.
Techniques of drilling are:
 - - Hand-augur drilling
 - - Water injection (jetting) drilling
 - - Rotary-percussion drilling
 - - Percussion drilling
 - - Sludge drilling.
 - - Rotary drilling

Drilled well cont...

- Drilled wells can get water from a much deeper level than dug wells can—often up to several hundred meters and smaller in diameter
- Drilled wells are typically created using either top-head rotary style, table rotary, or cable tool drilling machines, all of which use drilling stems that are turned to create a cutting action in the formation, hence the term drilling.

Drilled wells are usually cased with a factory-made pipe, typically steel (in air rotary or cable tool drilling) or plastic/PVC (in mud rotary wells, also present in wells drilled into solid rock).

Drilled well cont...

Hand-auger drilling :

- The cutting tool (known as the auger head) is rotated to cut into the ground, and then withdrawn to remove excavated material. The procedure is repeated until the required depth is reached. Note: This method is only suitable for unconsolidated deposits.

Advantages of hand-auger drilling:

- Inexpensive.
- Simple to operate and maintain.

Disadvantages of hand-auger

- **drilling:** Slow, compared with other methods. Equipment can be heavy.
- Problems can occur with unstable rock formations.
- Water is needed for dry holes.

Drilled well cont...

Jetting:

Water is pumped down the center of the drill-rods, emerging as a jet. It then returns up the borehole or drill-pipe bringing with it cuttings and debris. The washing and cutting of the formation is helped by rotation, and by the up-and-down motion of the drill-string. A foot-powered treadle pump or a small internal-combustion pump are equally suitable.

Advantages of jetting:

- The equipment is simple to use.
- Possible above and below the water-table.

Disadvantages of jetting:

- Water is required for pumping.
- Suitable for unconsolidated rocks only (e.g. sand, silt, clay) Boulders can prevent further drilling

Drilled well cont...

Sludging (reverse jetting)

Water flows down the borehole annulus (ring) and back up the drill pipe, bringing debris with it. A small reservoir is needed at the top of the borehole for recirculation. Simple teeth at the bottom of the drill-pipe, preferably made of metal, help cutting efficiency.

Advantages of sludging:

- The equipment can be made from local, low-cost materials, and is simple to use.

Disadvantages of sludging:

- Water is required for pumping.
- Suitable for unconsolidated rocks only. Boulders can prevent further drilling

Drilled well cont...

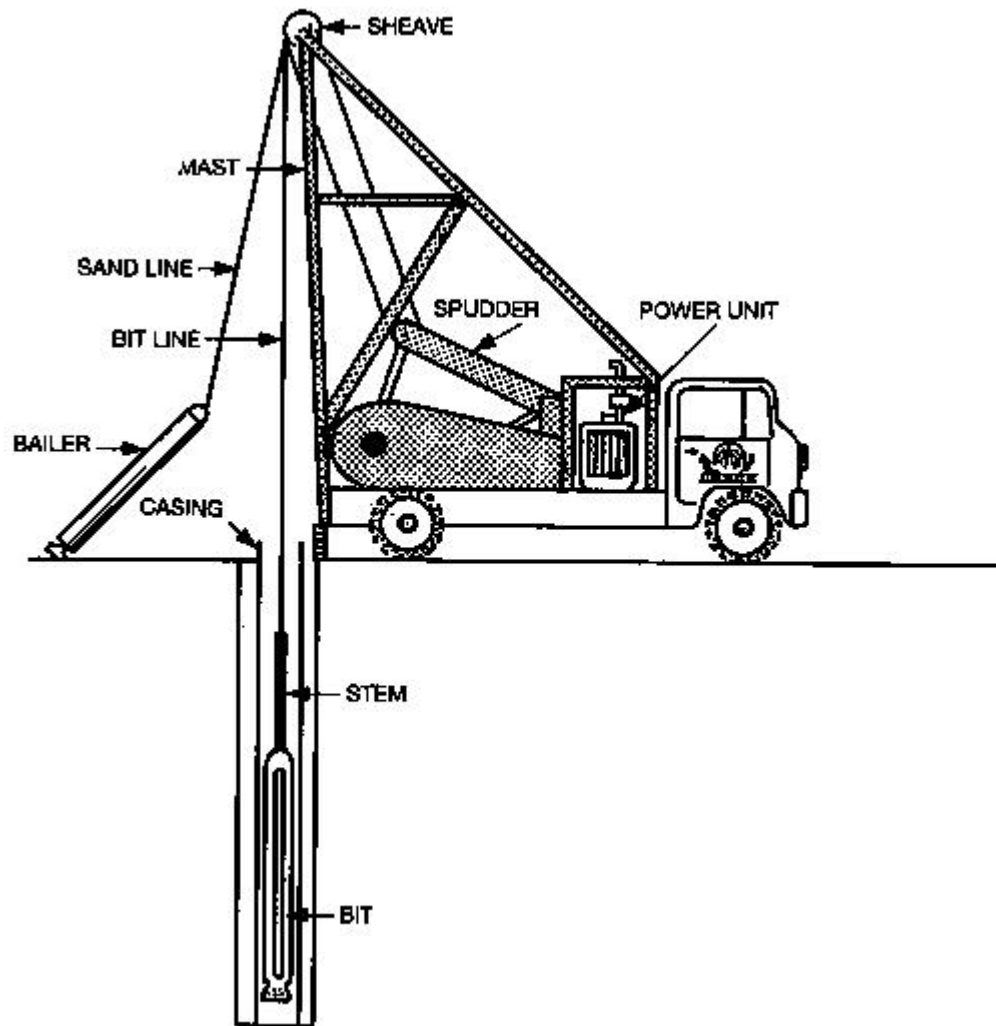
Rotary-percussion drilling: In very hard rocks, such as granite, the only way to drill a hole is to pulverize the rock, using 'down-the-hole hammer' (DTH). Compressed air is needed to drive this tool. The air also flushes the cuttings and dust from the borehole.

Advantages of rotary percussion

- drilling: Drills hard rocks.
- Possible to penetrate gravel.
- Fast.
- Operation is possible above and below the water-table.

Disadvantages of rotary-percussion drilling:

- Higher tool cost than other tools illustrated here.
- Air compressor required.
- Requires experience to operate and maintain



Drilled well cont...

Percussion drilling

- The lifting and dropping of a heavy (50kg+) cutting tool will chip and excavate material from a hole. The tool can be fixed to rigid drill- rods, or to a rope or cable.
- With a mechanical winch, depths of hundreds of meters can be reached

Advantages of percussion drilling:

- Simple to operate and maintain.
- Suitable for a wide variety of rocks.
- Operation is possible above and below the water-table.
- It is possible to drill to considerable depths.

Disadvantages of percussion drilling:

- Slow, compared with other methods.
- Equipment can be heavy.
- Problems can occur with unstable rock formations.
- Water is needed for dry holes to help remove cuttings

Tube wells cont...

2. Driven tube wells

- It consists of a pipe and well point which are forced into the water-bearing formation by driving with a wooden maul, drop hammer or other suitable means.
- They develop small yields and their construction is *limited to shallow depths in soft unconsolidated* formations free from boulders and other obstructions.
- They are commonly used for domestic water supply.
- Constructed by **driving a small-diameter, perforated tube with a pointed end into friable ground** like sand or gravel using a vertical to-and-fro movement
- Driven wells may be very simply created in unconsolidated material with a well or hole structure,

Driven well cont..

Techniques of driving:

- **Percussion** driving :percussion involves **driving a tube** with a pointed
- **Water injection** (or water jetting) driving : by injecting water under pressure inside a tube to facilitate digging the soil and removing the spoil.

3. Jetted tube wells

- It is constructed with hand-operated equipment or power-driven machines, depending upon the type of formation and the size and depth of the well. A hole in the ground is made by the cutting action of a stream of water.
- The water is pumped into the well through a pipe of small diameter. It is forced against the bottom of the hole through the nozzles of a jetting bit.
- The hole is cased to prevent a cave-in.
- Jetted tube wells have small yields and their construction is possible only in unconsolidated formations.

Based on Depth

1. Shallow tube wells

- are wells of low yield capacity(20 l/s).
- The average depth of the well is usually less than 60 m.
- Cavity tube wells and strainer tube wells with coir
- strainers generally fall in this category. The latter usually tap only the unconfined aquifer.

2. Deep tube wells

- Deep tube wells are wells of high capacity, tapping more than one aquifer.
- Their depth usually ranges from 60-300 m.
- May be strainer wells or gravel-pack wells
-

Based on type of aquifer

Tube wells under this category are classified as:

1. water table wells,
2. semi-artesian wells,
3. artesian wells and
4. hard rock bore wells.

- The classification is based on the location of the well and the characteristics of the aquifer.

- Wells may be defined as water table or artesian wells, depending upon whether they tap a water table aquifer or an artesian aquifer.

- Artesian wells are further classified as **semi-artesian wells** and **flowing artesian wells**.

Tube wells bored in hard rock formations are classified as hard rock bore wells.

Water table wells

- These are installed in unconfined aquifers which are under water table conditions, i.e. the water level is not under pressure. Generally, shallow tube wells fall under this category.

Semi-artesian wells

- Semi-artesian wells are installed under semi-artesian conditions of aquifer.
- The water is under pressure, but not so high as to flow out of the well.

Artesian wells

- A flowing well gets its supply from an aquifer where the water is under such high pressure that Water overflows at the top.
- The static water level in this case is above the ground surface and can be measured within the well casing, if the pipe is extended high enough so that the overflow does not occur.
- Alternatively, flow can be contained by capping the well casing, after which the shut-in head can be measured with a pressure gauge.

Multiple- well System

- A multiple-well system is a group of closely installed shallow tube wells, usually connected to a common header pipe or manifold and pumped by suction lift of a centrifugal pump.

Adapted under the following conditions:

- 1. Where the water table is at shallow depth
 2. Where the installation of medium and deep tube wells is not economical
 3. Where the hydraulic characteristics of the aquifer are poor
 4. Where salts are present in the deeper layers of the water-bearing formation
 5. Wherever there is a problem of waterlogging
 6. Where the conditions are such that a constant level of water is required to be maintained at some depth from ground surface.

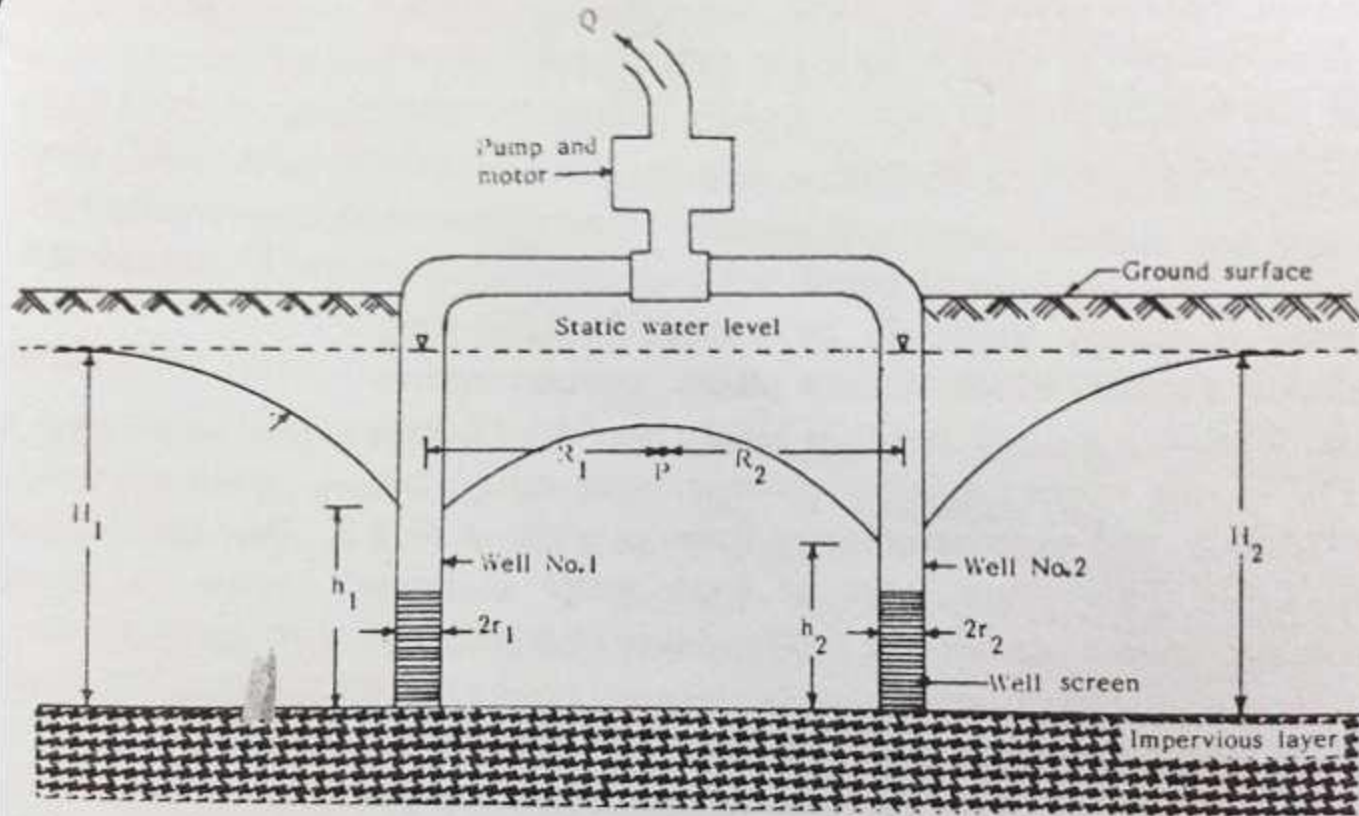
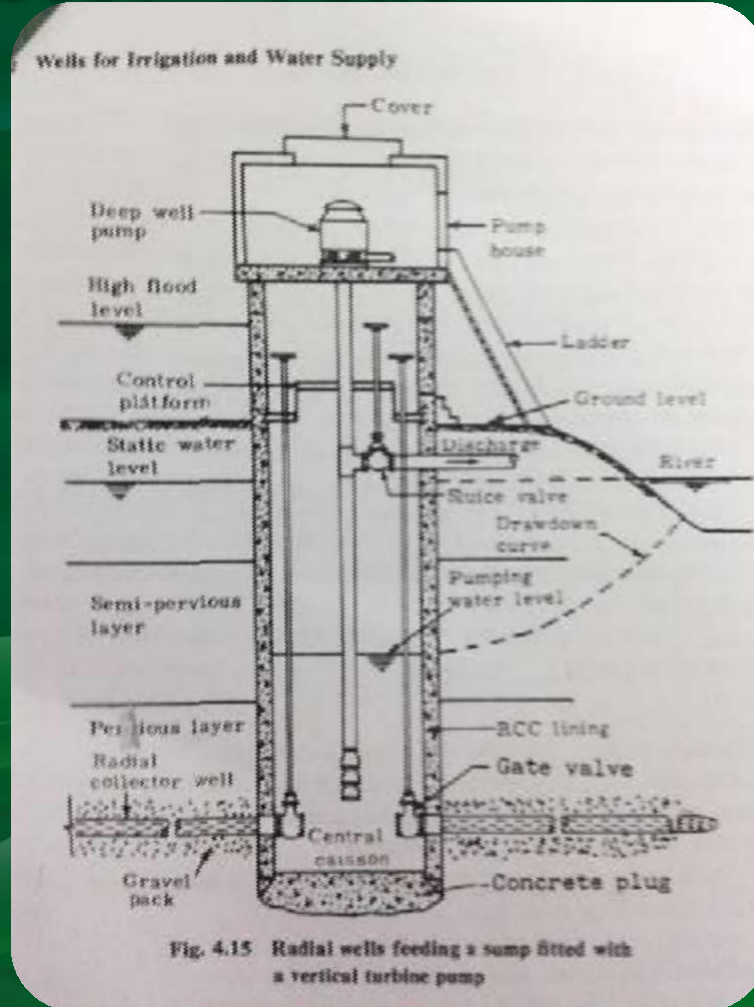


Fig. 4.14 Vertical section of two wells in an unconfined aquifer in a battery

Radial Collector Wells

- A radial collector well system comprises a series of horizontal wells discharging water into a central caisson.
- They are located at or close to rivers and other surface-water bodies.

Radial Collector Wells



Infiltration Gallery

- Infiltration galleries may be described as trenches dug in river beds
- Parallel to the axis of the river or transverse to it
- In which are laid perforated pipes or masonry-lined galleries with openings to permit the entry of water.
- Used in surface water pumping in rural water supply schemes

Infiltration Gallery

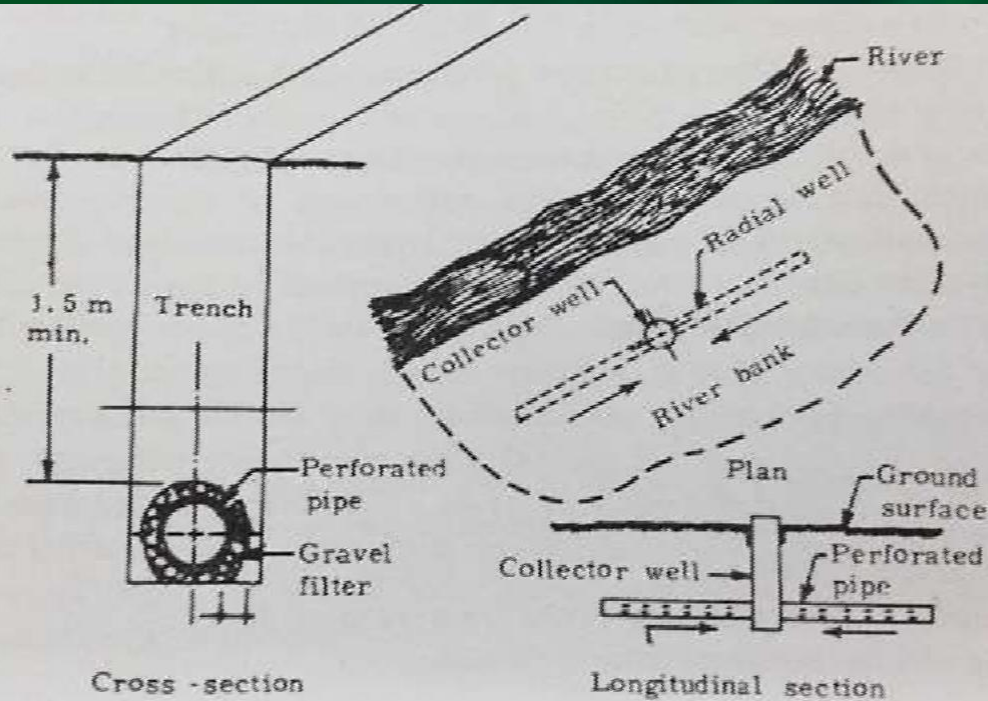


Fig. 4.16 Views of infiltration gallery lined with perforated pipe

Design of Tube Wells

Design of tube wells

- The design of a tube well involves the following steps:
 1. Mechanical analysis of samples of the underground formation obtained from various depths and the preparation of a well log.
 2. Design of housing pipe and well casing
 3. Design of well screen
 4. Design of gravel pack
 5. Design for sanitary protection

Analysis of particle size distribution of the aquifer

- Effective Size “ d_{10} ”
- The term ‘effective size’ is defined as formation particle size, where 10 per cent of the sand is finer and 90 per cent coarser.
- $d_{10} = 0.25 \text{ mm}$?
- 90% sand grains $> 0.25 \text{ mm}$
- 10 % sand grains $< 0.25 \text{ mm}$

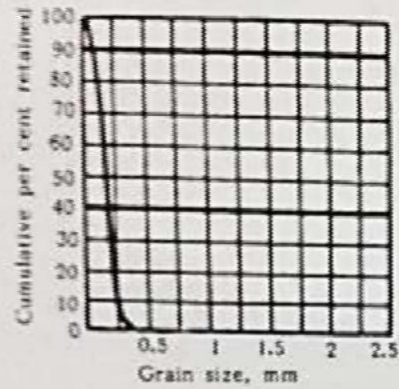
Uniformity coefficient, C_u

- This is the ratio expressing the variation in grain size of a granular material.

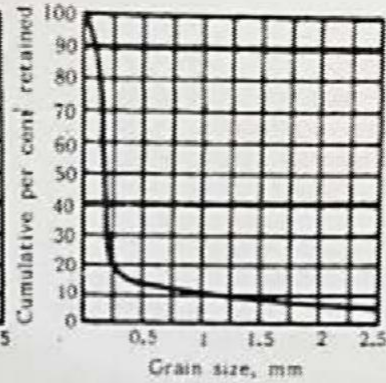
- $$C_u = \frac{d_{60}(\text{40\% retained})}{d_{10}(\text{90\% retained})}$$

- Uniform material,

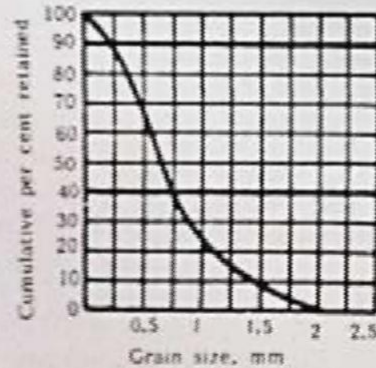
$$C_u < 2$$



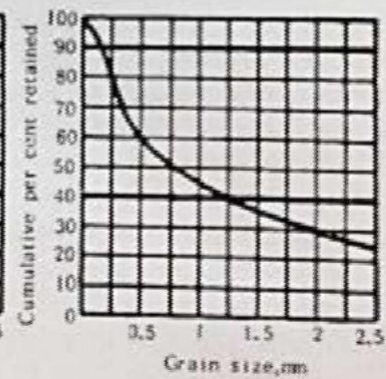
Class A curve: Fine Uniform sand, a poor aquifer, requires artificial gravel pack



Class B curve: Fine uniform sand with some coarse particles, artificial gravel pack optional



Class C curve: Well graded sand, good aquifer, no artificial gravel pack necessary



Class D curve: Sand and gravel mixture, rich aquifer, no artificial gravel packing required

Fig. 4.22 Typical sieve analysis curves of water bearing sands and gravels

Design of housing pipe and well casing

- Diameter of housing pipe
- should be at least 5 cm more in diameter than the nominal diameter of the pump.

Table 4.3 Diameter and Thickness of Housing Pipes of Tube Wells for Different Sizes of Turbine/Submersible Pumps

| <i>Discharge</i> l/min | <i>Nominal</i> <i>diameter of</i> <i>pump</i> cm | <i>Diameter of</i> <i>housing pipe</i> cm | <i>Thickness of</i> <i>housing pipe</i> mm |
|---------------------------|---|---|--|
| 475 | 12.5 | 15.0-20.0 | 1.5-3.5 |
| 1150 | 15.0 | 20.0-25.0 | 1.5-3.5 |
| 2275 | 20.0 | 25.0-30.0 | 2.0-3.5 |
| 4550 | 30.0 | 35.0 | 2.0-5.0 |
| 7500 | 35.0 | 40.0 | 2.0-6.0 |
| 11500 | 40.0 | 45.0 | 2.0-6.0 |

Source: Ahrens (1970)

Design of housing pipe and well casing

- Depth of housing pipe
 - Pump should be always submerged in water.
 - Pump must be set a few meters below the lowest drawdown level.

Design of housing pipe and well casing

- Diameter of Well casing pipe
 - Is fixed by the permissible velocity of water through the pipe.
 - Velocity may vary between – 1.5 to 4.5 m/s
 - Most suitable velocity – 2.5 to 3 m/s.
 - $a = Q/v$
 - $a = \pi d^2/4$
 - Where, Q = discharge, a = x-section area, d = diameter

Design of housing pipe and well casing

- Thickness of Well casing pipe
 - Steel pipes are produced in several thickness.
 - Heavier pipes – severe corrosive soil and water
 - Lighter pipes – mildly corrosive soil and water
 - Thickness of well casing is a function of the diameter and depth of the well.

Table 4.4 Suggested Thickness of Well Casing Pipe, mm

| Depth of well m | Diameter of well casing, cm | | | | |
|--------------------|-----------------------------|------|------|------|------|
| | 15 | 20 | 25 | 30 | 35 |
| 0-10 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 10-20 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 20-30 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 30-40 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 40-50 | 1.59 | 1.59 | 1.98 | 1.98 | 2.78 |
| 50-60 | 1.59 | 1.98 | 1.98 | 2.78 | 2.78 |
| 60-70 | 1.98 | 1.98 | 1.98 | 2.78 | 2.78 |
| 70-80 | 1.98 | 1.98 | 1.98 | 2.78 | 3.57 |
| 80-90 | 1.98 | 1.98 | 2.78 | 2.78 | 3.57 |
| 90-100 | 1.98 | 2.78 | 2.78 | 3.57 | 3.57 |
| 100-110 | 1.98 | 2.78 | 3.57 | 3.57 | 3.57 |
| 110-120 | 1.98 | 2.78 | 3.57 | 3.57 | 4.76 |
| Above 120 | 2.78 | 3.57 | 3.57 | 4.76 | 4.76 |

Source: Ahrens (1970)

Bore size and well depth

- Bore

- size

- At least 5 cm bigger in diameter than the casing pipe If Gravel pack used

- Bore size = outside dia of casing pipe + (2 x gravel pack thickness)

- Well depth

- Depends upon the locations of water-bearing formations
- Desired yield of the well
- Economic considerations
- Hydraulic conductivity of the aquifer material

Selection of strata to be screened

- Permeability of the aquifer $a (d_{10})^2$ (for
- same C_u) Low C_u = more permeable
- aquifer (for same d_{10})
- Thick and homogeneous unconfined aquifer-
lower 1/3rd thickness screened
- Thick and homogeneous confined aquifer-
central 80-90% thickness screened

Design of well screen

- The basic requirements of a well screen are
 - i. It should be resistant to corrosion and deterioration
 - ii. It should be strong enough to prevent collapse
 - iii. It should offer minimum resistance to the flow of water
 - iv. It should prevent excessive movement of sand into the well

Design of well screen

Slot Opening

- Well screen slot openings is determined by matching the size of the opening with the grain-size distribution of the material surrounding the screen.
- Slot size varies from as low as 0.2 mm to as large as 5mm
- a) Non-Gravel-Pack wells
 - For Homogeneous and non corrosive aquifer- slot opening - d_{60}
 - For Homogeneous and corrosive aquifer- slot opening - d_{50}
 - Optimum size --- 40% line intersects the sample-analysis curve— screen opening from the horizontal scale--- d_{60}
- b) Gravel-Pack Wells
 - Slot opening - $d_{10} \pm 8\%$

Design of well screen

● Percent Open Area

- It is desirable to provide an open area of about 20 per cent for well screens .

● Diameter of the Screen

- Should produce a screen entrance velocity of not more than 3 cm/s
- Maximum entrance velocity – 5 cm/s (sufficient sand thickness)

Diameter of the Screen

Table 4.5 Recommended Diameter of Casing Pipe and Well Screen

| <i>Discharge</i> l/min | <i>Casing pipe/screen diameter, cm</i> | |
|---------------------------|--|--------------------|
| | <i>Minimum</i> | <i>Recommended</i> |
| .475 | 10 | 10 |
| 475-1125 | 15 | 15 |
| 1125-3000 | 20 | 25 |
| 3000-5250 | 25 | 30 |
| 5250-9500 | 30 | 35 |
| 9500-13300 | 35 | 40 |

Source: Ahrens (1970)

Screen Length

- Water table aquifers

- Bottom $\frac{1}{3}$ to bottom $\frac{1}{2}$ of aquifer may be screened

- Artesian Aquifer

- 75-90 per cent of the thickness of the aquifer may be screened

At least 30 cm of aquifer depth at the top and bottom of the screen should be left unscreened to safeguard against an error in the placement of screen during installation.

Screen Length

- Minimum length of screen:
- For a non-gravel pack well is designed on the basis of the following equation

$$h = \frac{Q}{A_0 V_e}$$

- Where,
 - h = minimum length of the well screen, m
 - Q_0 = maximum expected discharge capacity of well, m^3/min
 - A_0 = effective open area per meter length of the well screen, m^2
 - V_e = entrance velocity at the screen, m/min

Design of Gravel Pack

- The term gravel packing refers to the placing of gravel around the well screen.
- The artificial gravel packing may be used under following conditions:
 1. To stabilize fine-grained, poorly-sorted sand aquifers and to avoid sand pumping.
 2. To permit the use of larger slot openings and the resultant higher well efficiency in fine-grained aquifers.
 3. The use of an artificial gravel pack will permit the use of a single slot-size screen and eliminate the positioning problem in formation of alternating zones of coarse and fine aquifer material.

Design criteria for gravel pack

- The mean grain size of the pack material bears a specific relationship to the mean grain size of the formation material.
- PA ratio =
$$\frac{50\% \text{ size of gravel pack}}{50\% \text{ size of aquifer}}$$

a) Uniform aquifer ($C_u \leq 2$)

PA ratio = $\frac{50\% \text{ size of gravel pack}}{50\% \text{ size of aquifer}}$ should lie between 9 and 12.5

b) Graded Aquifer ($C_u \geq 2$)

PA ratio = $\frac{50\% \text{ size of gravel pack}}{50\% \text{ size of aquifer}}$ should lie between 12 and 15.5

Gravel Pack Material

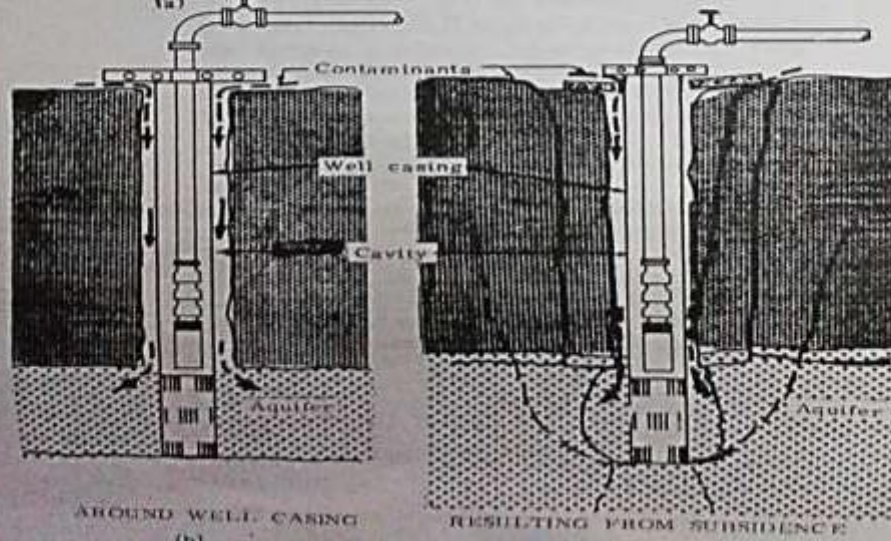
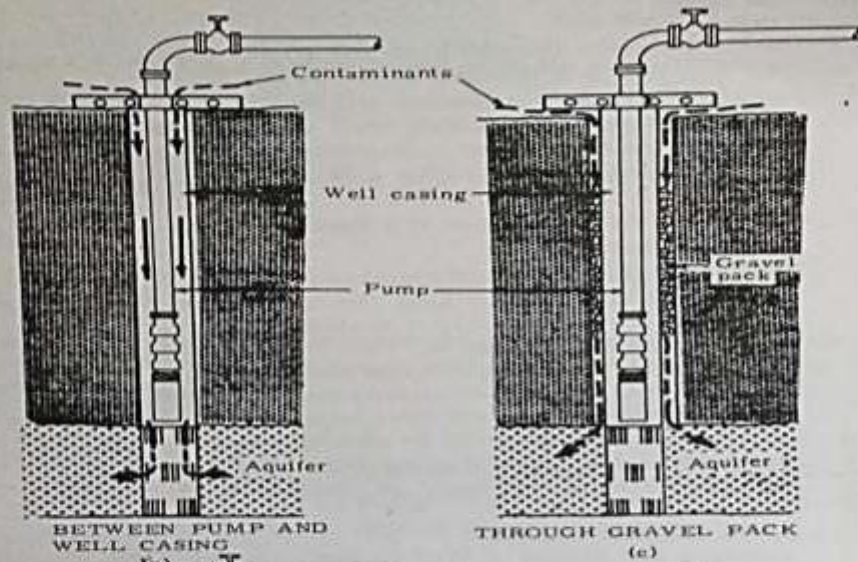
- The following are the desirable characteristics of a good gravel material
 1. It should be clean
 2. The grains should be smooth and round (flat particles should be avoided)
 3. It should be a hard, insoluble, siliceous material with less than 5 per cen calcareous particles (limestone). Particles of shale and gypsum are undesirable.
 4. It should be uniform in size.

Screening of Gravel:

- The gravel-pack material may be screened first through the screen with the larger openings to remove over-size particles,
- and then through the screen with smaller openings to screen out the under size particles.

Sanitary Protection of Tube Wells

- The following are the common paths of entry of contaminated surface water into the tube well:
 1. Between the pump and the well casing
 2. Around the well casing
 3. Improperly placed gravel pack
 4. Reverse flow through the pump
 5. Subsidence of the soil or aquifer around the well casing due to sand pumping.



- Protecting the top section of a tube well from entry of contaminants
- Grouting and sealing of well casing

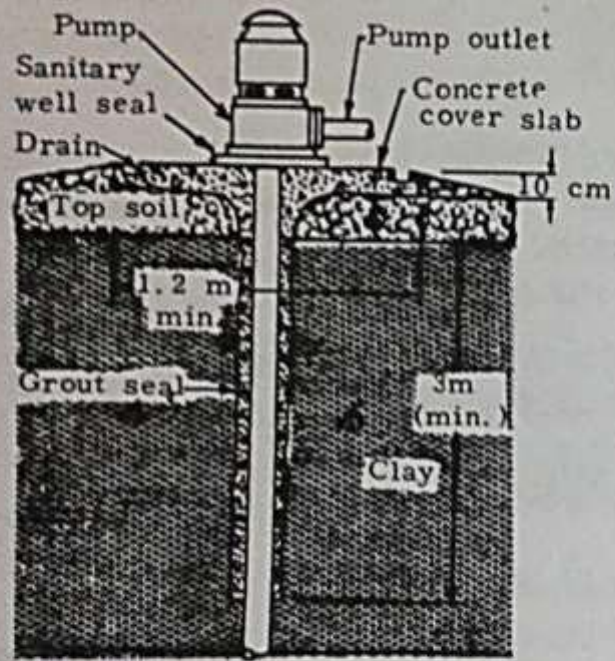


Fig. 4.28 Sanitary protection of the top section of a tube well

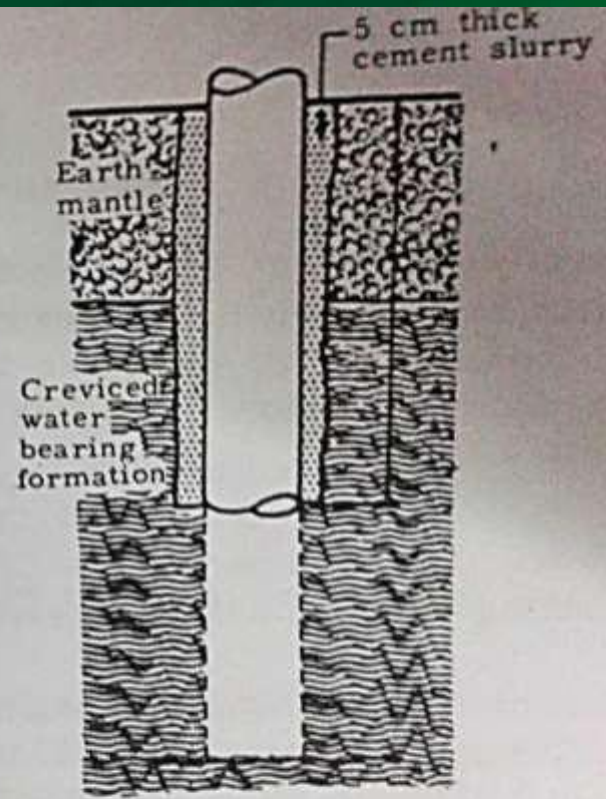


Fig. 4.29 Sanitary protection of bore wells drilled in hard rock formations with earth mantle less than 8 m thick

Development and Testing of Tube Wells

Tube-well Development

The development of tube well is essential process to obtain an efficient and long -lasting well.

Development of a tube well involves removal of finer material from around the well screen, thereby enlarging the passages in the water-bearing formation to facilitate entry of water.

Development increases the effective radius of the well and, consequently, its yield.

objectives of well development

1. Repair to damage done to the formation by drilling operation and restore the original hydraulic conductivity of the aquifer.
2. To increase the porosity and permeability of the water bearing formation in the vicinity of the well by removing finer material of aquifer.
3. To stabilize the formation around well screen to yield sand free discharge.

Methods of well development

1. Over pumping
2. Surging with surge block or boiler
3. Surging and pumping with air-compressor
4. Back washing
5. High velocity jetting
6. Aquifer development techniques:
7. Use of explosive
8. Use of acid

SUMMARY OF RECOMMENDATIONS FOR DEVELOPMENTS OF VARIOUS TYPES OF WELLS

| Sl. No | Method of Development | Tubewell Up to and Including 150 m in Alluvial | | Tubewell Above 150 Up to and Including 300 m in Alluvial | | Tubewell Above 300 Up to and Including 800 m in Alluvial | | Boulders and Febbles | Hard Rock (DTH) | Remarks |
|--------|-----------------------|--|--------------|--|----------------|--|--------------------|----------------------|-----------------|---|
| | | Artificial Gravel Pack | Natural Pack | Artificial Gravel Pack | Natural Pack | Artificial Gravel Pack | Natural Pack | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| i) | Over pumping | Effective | Effective | Satisfactory | Satisfactory | — | — | Most effective | Most effective | In case of hard rock areas only pumping at normal discharge should be carried out |
| ii) | Compressed air | Satisfactory | Satisfactory | Satisfactory | Satisfactory | Not very effective | Not very effective | Satisfactory | — | Over pumping should follow the development with air compressor wherever needed |
| iii) | High velocity jetting | Satisfactory | Satisfactory | Very effective | Very effective | Very effective | Very effective | Not effective | Not effective | Simultaneous pumping of silt and clay with air compressor is recommended |
| iv) | Surge Block | Satisfactory | Satisfactory | Satisfactory | Satisfactory | Satisfactory | Satisfactory | — | — | This is not recommended where streaks of clay and fine sand formation are encountered |
| v) | Explosives | — | — | — | — | — | — | — | Effective | This usually increases the capacity of water veins and fractures |

Thanks

CHAPTER FIVE

GROUNDWATER WELLS DESIGN

5.1 Objectives

To produce a combination of longevity, performance and cost effectiveness. Proper design reduces the risk of well failure, and thereby provides greater assurance that the well will satisfy the intended purposes. The main aims are:

- ✓ To obtain the design yield with minimum drawdown consistent with aquifer capability and economic optimization of the well;
- ✓ Good quality water with proper protection from contamination;
- ✓ Water that remains solid-free;
- ✓ A well with a long life (more than 25 years);
- ✓ Reasonable capital and operational costs.

The main points in designing a well are:

- ✓ Choice of well location;
- ✓ Selection of appropriate drilling method;
- ✓ Selection of appropriate construction materials, including pump specification;
- ✓ Proper dimensional factors of borehole and well structure;
- ✓ Geological and geophysical logging, water quality sampling and test-pumping can be carried out in a satisfactory way;
- ✓ The well pumping rate should satisfy the demand for water;
- ✓ The inflow sections of the well should be designed opposite those permeable geological formations;
- ✓ Well design should be such that pollutants from land surface or other sources can not enter the well;
- ✓ Materials used in the well should be resistant to corrosion and possess sufficient strength to prevent collapse
- ✓ Well design should be based on low installation and running costs while not affecting well performance.

5.2 Introduction

In the field of groundwater hydrology, major attention has been devoted to the development and application of aquifer hydraulics, but unfortunately, much less consideration is given to the well structure itself. Although substantial effort may be expended on aquifer testing and computations to quantify the groundwater withdrawal, successful operation of the system may not be achieved if the well is not properly designed. In many instances, the project hydrogeologist or contractor has only a cursory knowledge of screen entrance velocity criteria, and artificial gravel filters are often designed solely on the basis of other previously installed wells in the area. This lack of attention to proper design can result in inefficient well, requiring frequent cleaning and redevelopment, that is ultimately of limited usefulness to the owner.

Water well is a hole or shaft, usually vertical, excavated in the earth for bringing groundwater to the surface. Occasionally wells serve other purposes, such as for subsurface exploration and observation, artificial recharge, and disposal of wastewaters. Many methods exist for constructing wells; selection of a particular method depends on the purpose of the well, the quantity of water required, depth to

groundwater, geologic conditions, and economic factors. Attention to proper design will ensure efficient and long-lived wells.

5.3 Steps of Designing a Well

The following steps should be followed so as to design a well:

1. Determine the yield required;
2. Identify formation with potential to support this yield;
3. Identify drilling method;
4. Identify aquifer type;
5. Determine depth of borehole;
6. Determine minimum well diameter;
7. Determine maximum discharge vs. drawdown;
 - ✓ If $Q > \text{yield}$, then reduce diameter of the well.
 - ✓ If $Q < \text{yield}$, then drill another well (discuss the matter financially!!!)
8. Determine dimensions of pump chamber;
9. Determine screen and filter characteristics (see if you need filter at all!!!)
10. Determine pump characteristics including stages and pumping rate

5.4 Information Required for Well Design

Information required before design can be completed includes:

Aquifer location

- depth to water bearing strata, and
- thickness of strata (aquifer thickness).

Aquifer nature:

- consolidated or unconsolidated material,
- hard or friable rock,
- confined or unconfined,
- leaky or with delayed yield, etc.

Aquifer parameters:

- hydraulic conductivity,
- transmissivity,
- storativity,
- grain size,

Location of aquifer boundaries;

Aquifer recharge characteristics;

Nature of formations above aquifer;

The need for this type of data is:

1. to establish where the intake parts of the well should be located;
2. to design the type of well casing required to ensure that the borehole remains stable and does not collapse;

3. to allow computation of likely drawdown in the well, and so determine the location of the pump intake. This in turn controls the diameters and length of upper well casing.

5.5 Well Structure

The main elements to well structure are the housing and the well screen at the intake zone where the water enters the well. The components (see **Figure 5.1**) that need to be specified in a properly designed well include:

1. **Upper Well Casing and Pump Housing** (prevents hole collapse, keeping the borehole and conduit open.)
 - ✓ Length;
 - ✓ Diameter;
 - ✓ Materials;
 - ✓ Thickness.
2. **Well Screen** “where required” (enables water, but not aquifer material, to enter the well which enables development and/or rehabilitation of the well, and structurally supports the well in loose formation materials)
 - ✓ Location in well;
 - ✓ Length;
 - ✓ Diameter;
 - ✓ Slot types;
 - ✓ Open area (slot dimensions);
 - ✓ Materials;
 - ✓ Thickness;
3. **Filter or Gravel Pack** “where required” (enables good flow to the well, without pumping fine-grained materials)
 - ✓ Material;
 - ✓ Grading;

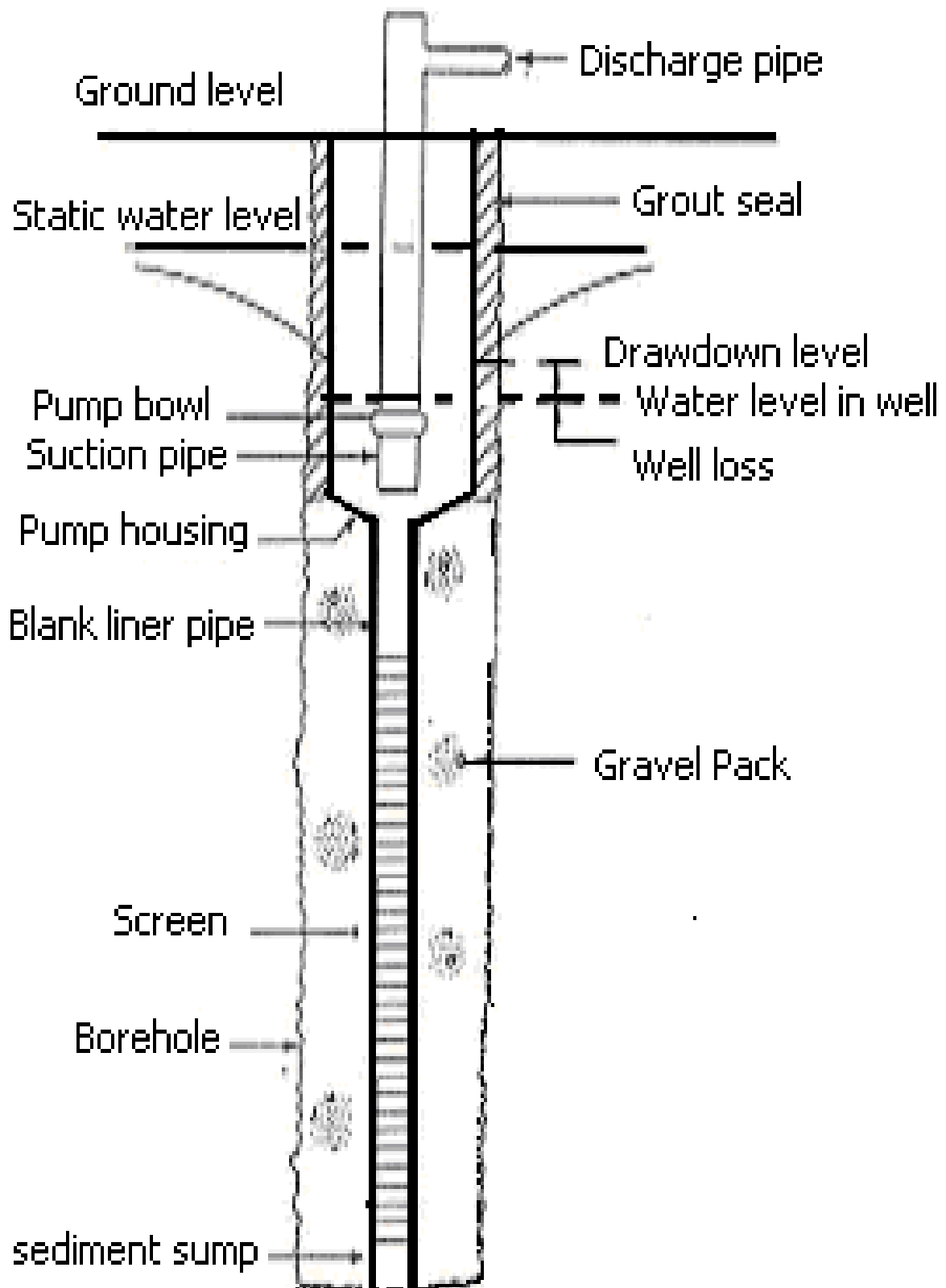


Figure 5.1 Components of a typical well

5.6 Upper Well Casing and Pump Housing

5.6.1 Length of Casing

The length of the upper casing is controlled by the requirements of the pump. The pump usually needs to remain submerged, with the minimum submergence recommended by the manufacturer.

The “operating” water level in the well can be calculated as the distance below ground level of the static piezometric level “static water level” (**H**) less the anticipated drawdown at the well (**s_w**) less a safety margin(**SF**).

The anticipated well drawdown (**s_w**) is usually calculated for steady state conditions, as a function of the well design discharge and the aquifer transmissivity (or the product of the screen length and the aquifer permeability).

The Safety margin (**SF**) should include allowance for:

- ✓ The variation in aquifer transmissivity due to aquifer heterogeneity;
- ✓ Well deterioration;
- ✓ Well energy losses (arising from flow through the screen and gravel pack);
- ✓ Future contingencies for well interference, seasonal or over-year decline in static water levels etc.;

So, the length of the upper casing becomes;

$$L = H + S_w + SF + PR \quad (5.1)$$

Where,

| | | |
|----------------------|--|---------|
| L | length of the upper casing | (m) |
| H | depth to static water level | (m bgl) |
| S_w | anticipated drawdown | (m) |
| SF | Safety margin (safety factor) | |
| PR | Pump requirements that includes: | |
| | ✓ Pump submergence to the impeller inlet; plus | |
| | ✓ Length of pump below this point; plus | |
| | ✓ Manufacturer’s recommended clearance below this point; | |

The consequences of making inadequate provision for lower pumping water levels than anticipate by having too short an upper casing is serious in that a reduced discharge must be accepted or the well must be re-drilled.

Sometimes the upper well casing is extended to the aquifer top, but the cost of this exercise is often prohibitive.

5.6.2 Diameter

The diameter of upper well casing required is that needed to accommodate the pump, with some margin for clearance around the unit.

Manufacturers of pump will recommend a “minimum” casing (see **Table 5.1**). The diameter must be large enough for the pump to be a comfortable fit, making allowances for non-verticality of the borehole. A diameter 100 mm larger than the nominal pump diameter is often recommended. In general, the vertical velocity within the well casing needs to be less than 1.5-2 m/sec to minimize well losses.

Table 5.1 Recommended well Diameters for various pumping rate* (after Driscoll, 1989)

| Anticipated Well Yield m ³ /day | Nominal Size of Pump Bowls | | Optimum Size of Well Casing | | Smallest Size of Well Casing | |
|---|-------------------------------|-----|--------------------------------|--------|---------------------------------|--------|
| | in | mm | in | mm | in | mm |
| Less than 545 | 4 | 102 | 6 ID | 152 ID | 5 ID | 127 ID |
| 409 - 954 | 5 | 127 | 8 ID | 203 ID | 6 ID | 152 ID |
| 818 - 1,910 | 6 | 152 | 10 ID | 254 ID | 8 ID | 203 ID |
| 1,640 - 3,820 | 8 | 203 | 12 ID | 305 ID | 10 ID | 245 ID |
| 2,730 - 5,450 | 10 | 254 | 14 OD | 356 OD | 12 ID | 305 ID |
| 4,360 - 9,810 | 12 | 305 | 16 OD | 406 OD | 14 OD | 356 OD |
| 6,540 - 16,400 | 14 | 356 | 20 OD | 508 OD | 16 OD | 406 OD |
| 10,900 - 20,700 | 16 | 406 | 24 OD | 610 OD | 20 OD | 508 OD |
| 16,400 - 32,700 | 18 | 508 | 30 OD | 762 OD | 24 OD | 610 OD |

One should recognize that:

- For specific pump information, the well-design engineer should contact a pump supplier, providing the anticipated yield, the head conditions, and the required pump.
- The size of the well casing is based on the outer diameter of the bowls for vertical turbine pumps, and on the diameter of either the pump bowls or the motor for submersible pumps.

Moreover, the casing diameter is also based on the size of the bit used in drilling the borehole. **Figure 5.2** shows the relationship between hole and casing diameter.

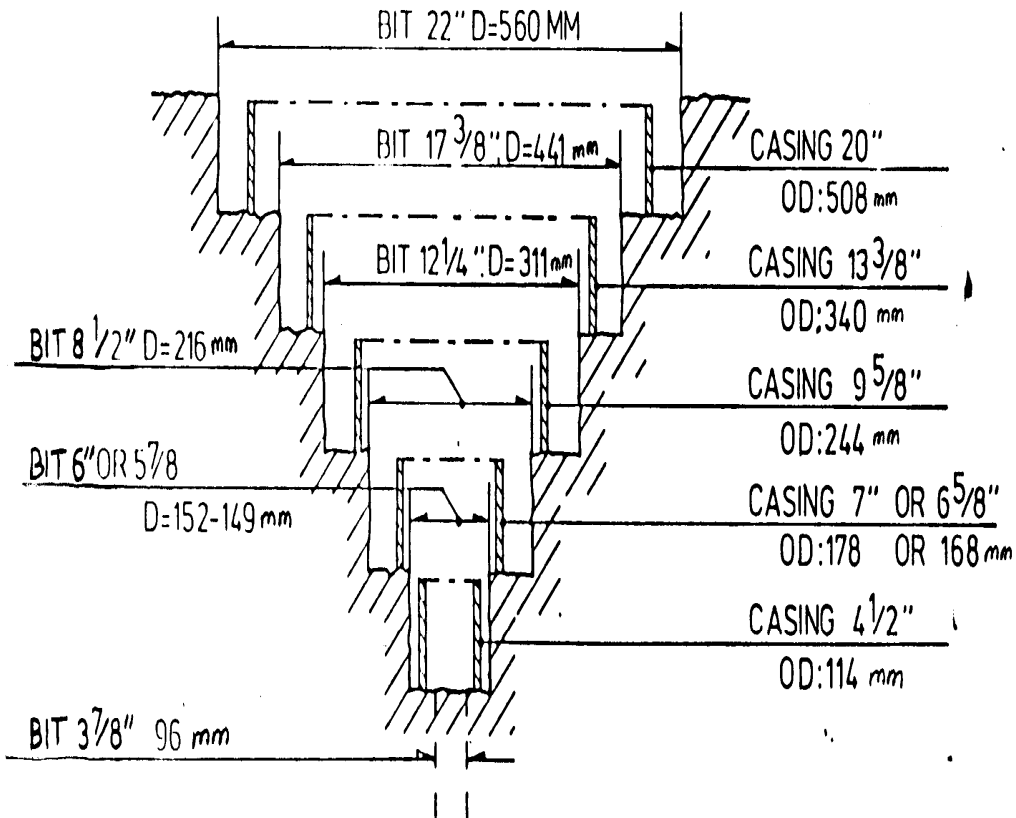


Figure 5.2 Hole and casing diameter

5.7 Well Screen and Lower Well Casing

Lower well casing and screen is used:

- ✓ To give the formation support (prevent well collapse)
- ✓ To prevent entry of the fine aquifer material into the well
- ✓ To reduce loss of drilling fluids
- ✓ To facilitate installation or removal of other casing
- ✓ To aid in placing a sanitary seal
- ✓ To serve as a reservoir for a gravel pack

For well screen design it is necessary to consider the following points:

- ✓ Minimum entrance velocity
- ✓ Maximum open area of screen
- ✓ Correct design of slot to fit aquifer or gravel pack material
- ✓ Periodic maintenance
- ✓ Selection of screen material for corrosion resistance

5.7.1 Screen Length and Location

The optimum length of well screen for a specific well is based on aquifer thickness, available drawdown, stratification within the aquifer, and if the aquifer is unconfined or confined. Criteria for determining the screen length for homogeneous and heterogeneous, confined and water-table aquifer wells are described in the following sections.

The basic design principle is to screen the whole aquifer as a first assumption. This approach is inefficient in:

- Very thick aquifers – use existing developments to have some guidelines (either local “rules of thumb” indicating a certain length of screen per unit discharge or data to use in equations to calculate optimum screen length for a specified discharge)
- Shallow unconfined aquifers – upper well casing is likely to occupy much of the aquifer thickness. The relative dimensions of the upper and lower parts of the well will be dependent upon the relative importance of well efficiency and maximum yield.

Partial penetration of the well-screen will be less efficient (see **Figure 5.3**). Costs of additional screen must be balanced against the benefits of reduced drawdown.

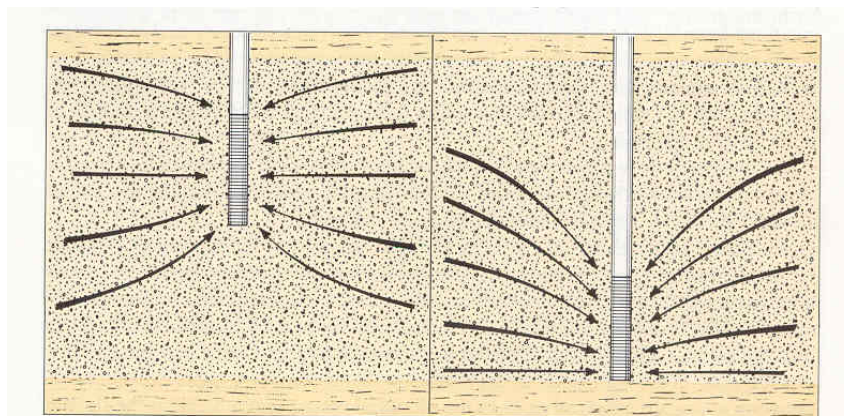


Figure 5.3 partial penetrations when the intake portion of the well is less than the full thickness of the aquifer. This causes distortion of the flow lines and greater head losses.

Field identification of screenable aquifer will largely be made on the basis of the lithological log. Clays and unproductive sections are usually screened as blank casing is cheaper than screen. Unconsolidated formations with grain size less than the “design” formation must be cased out (see **Figure 5.4**). This:

- Protects the material from being eroded thereby placing the casing under stress.
- Protects the pump from the ill effects of pumping sand.

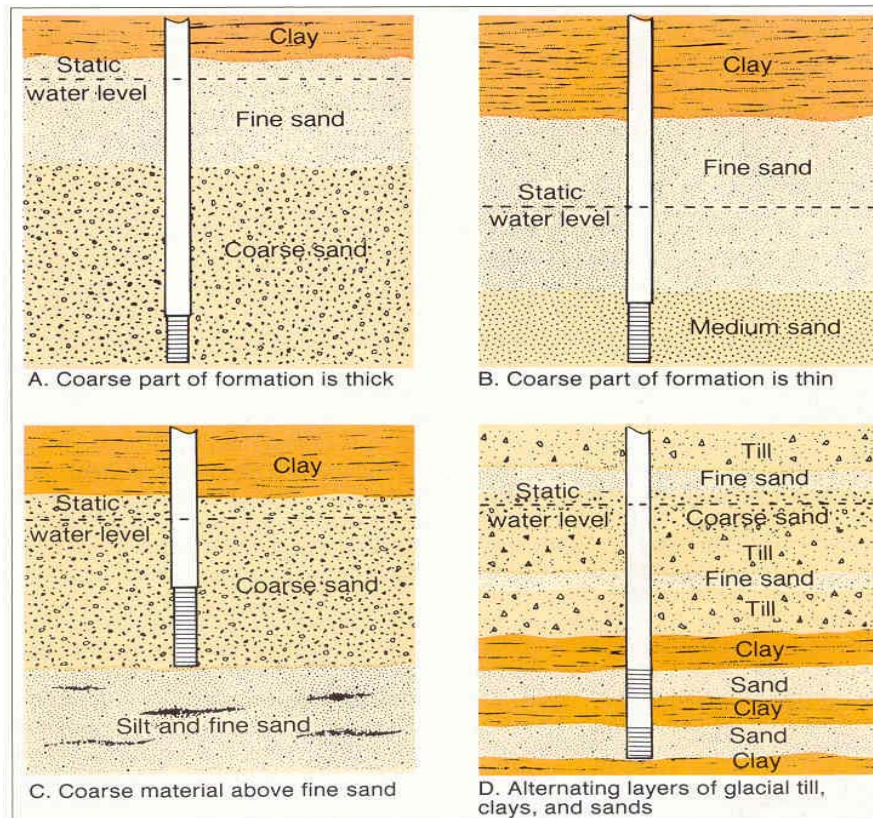


Figure 5.4 Suggested positioning of well screens in various stratified water-bearing formations

Homogeneous Confined (Artesian) Aquifer

The maximum drawdown in wells in confined aquifers needs to be limited to the top of the aquifer. Provided the pumping level will not induce drawdown below the top of the aquifer (the aquifer does not become unconfined), **70 to 80 percent** of the thickness of the water-bearing unit can be screened.

The general rules for screen length in confined aquifers are as follows:

- If the aquifer thickness is less than 8 m, screen 70% of the aquifer.
- If the aquifer thickness is (8 - 16) m, screen 75% of the aquifer.
- If the aquifer thickness is greater than 16 m, screen 80% of the aquifer.

In many applications, fully screening a thick, generally uniform aquifer would be prohibitively expensive or would result in rates of entrance velocity through the well screen that were too slow. Therefore, for best results, the screen section needs to be centered or divided into sections of equal length and interspersed with sections of blank pipe to minimize convergence of flow lines that approach the well bore, and improve well performance (**Figure 5.5**).

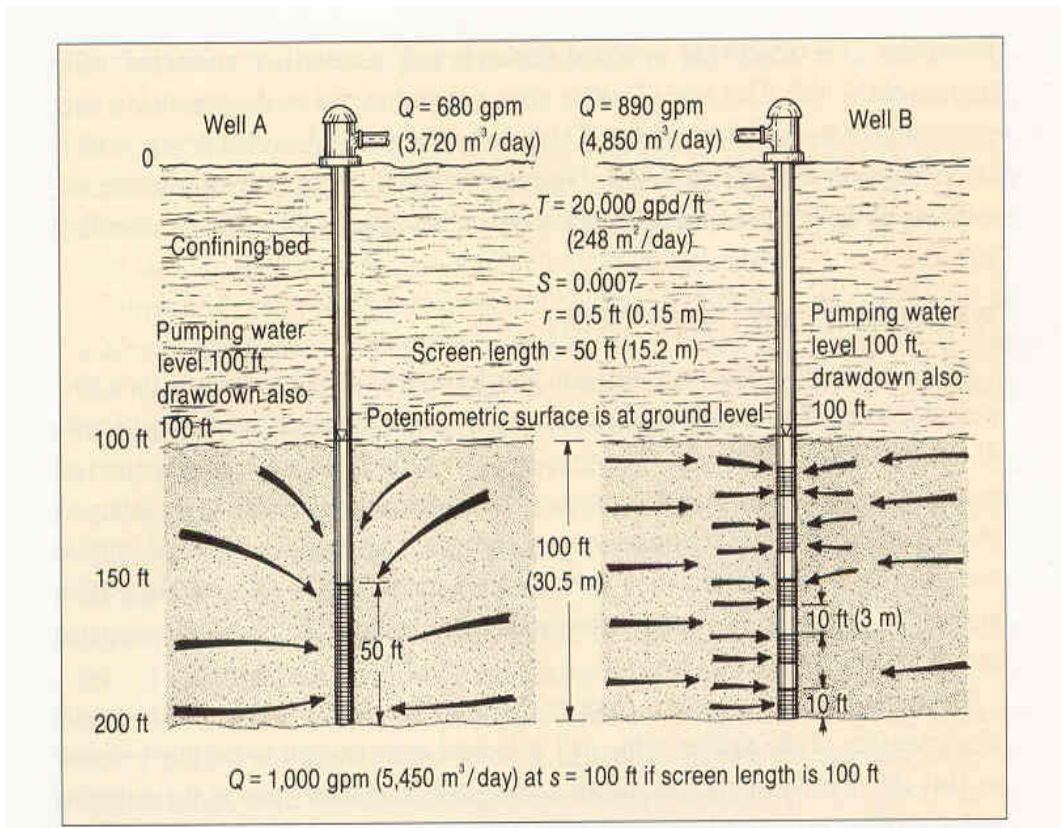


Figure 5.5 Flow line convergence to a screened interval is minimized and well performance can be improved by using sections of well screen in a thick aquifer to reduce the effect of partial penetration. Total screen length is the same in both wells.

Heterogeneous Confined (Artesian) Aquifer

In heterogeneous or stratified confined aquifers, the most permeable zones need to be screened; these zones can be determined by one or several of the following methods:

- Permeability tests (falling head and constant head tests)
- Sieve analysis and comparison of grain-size curves.
 - ✓ If the slopes of the grain-size curves are about the same, the relative permeability of two or more samples can be estimated by the square of the effective size of each sample. For example, sand that has an effective grain size of 0.2 mm will have about 4 times the hydraulic conductivity of sand that has an effective grain size of 0.1 mm.
 - ✓ If two samples have the same effective size, the curve that has the steepest slope usually has the largest hydraulic conductivity.
- Well-bore velocity surveys, if feasible, to start well production prior to completion or to install an extended section of perforated casing or screen in the borehole;
- Interpretation of borehole geophysical logs;

In heterogeneous or stratified aquifers, (80-90) % of the most permeable layers needs to be screened.

Homogeneous Unconfined (Water-Table) Aquifer

- Screening the bottom one-third of the saturated zone in a homogeneous unconfined aquifer normally provides the optimum design.
- In some wells, screening the bottom one-half of the saturated layers may be more desirable for obtaining a larger specific capacity (if well efficiency is more desirable than the maximum yield).
- In water-table wells, larger specific capacity is obtained by using as long screen as possible; therefore, convergence of flow lines and the entrance velocity through the well screen are minimized. However, there is more available drawdown when a shorter screen is used.

5.7.2 Well Screen Diameter

A rule of thumb is that the upflow velocity limit of **1.5 m/s** will produce a well with reasonable upflow losses.

Screen Diameter Design Procedures

- Design on upflow losses – select a screen size that reduces these to a value of a few percent of the overall pumping head (or the economic optimum size);
- Screen sizes usually standard, in increments of about 1 in. for small sizes and 2 in. above 6 in. diameter.
- If the cost of increasing diameter is significant, and no significant reduction in upflow losses accrues, use of large diameter would only be advised if the following are recognized problems in the area:
 - well deterioration
 - encrustation
 - screen corrosion
- The screen diameter is selected to fulfill the essential principle: the total area of the screen openings needs to be provided so the entrance velocity will not exceed the design standard. Diameter can be varied after length and size of the screen openings have been selected. Frequently, the length of the screen and the slot size are fixed by the natural characteristics of the formation; thus screen diameter is the main variable.
- Laboratory tests and experience indicate that if the screen entrance velocity is maintained at about 0.03 m/sec:
 - Frictional losses in screen openings will be negligible.
 - The rate of incrustation will be minimized.
 - The rate of corrosion will be minimized.
- The entrance velocity is equal to the expected or desired yield divided by the total area of openings in the screen. If the entrance velocity is greater than 0.03 m/sec. the screen diameter needs to be increased to provide sufficient open area so the entrance velocity is about 0.03 m/sec. The pump needs to be set above the top of the screen for these designs.

5.8 Slot Types and Open Area

Well screens are manufactured from a variety of materials and range from crude hand-made contrivance (**Figure 5.6**) to highly efficient and long life models made on machines costing hundreds of thousands of dollars (**Figure 5.7**). The value of a screen depends on how effectively it contributes to the success of a well. Important screen criteria and functions are discussed before as:

1. Criteria
 - Larger percentage of open area
 - Nonclogging slots
 - Resistant to corrosion
 - Sufficient column and collapse strength
2. Functions
 - Easily developed
 - Minimal incrusting tendency
 - Low head loss through the screen
 - Control sand pumping in all types of aquifers

Maximizing each of these criteria in constructing screens is not always possible depending on the actual screen design. For example, the open area of slotted casing cannot exceed (11-12) % or the column strength will be insufficient to support the overlying casing during screen installation. However, open areas of 30 to 50 percent are common for continuous-slot screens with no loss of column strength. In high corrosive waters, the use of plastic is desirable, but its relatively low strength makes its use impractical for deep wells.

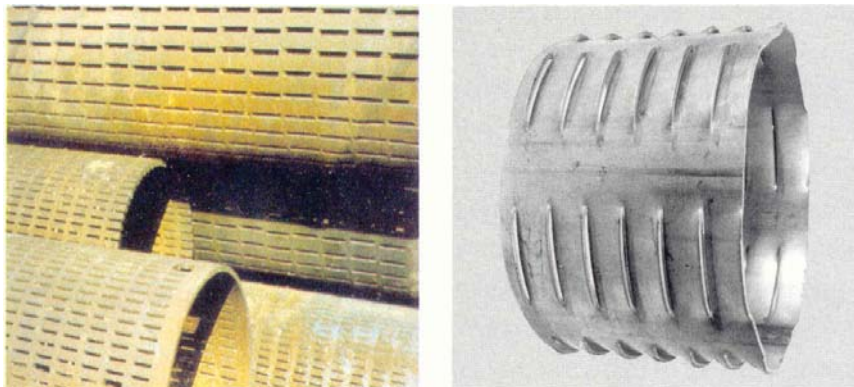


Figure 5.6 Some screen openings are produced by hand cutting and by punching holes or louvers in casing.

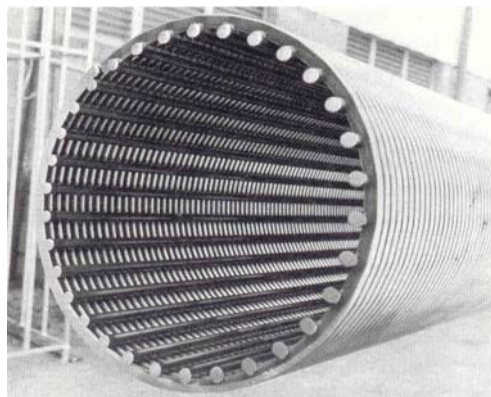


Figure 5.7 Continuous-slot screens are widely used for water wells. They are constructed by winding cold-rolled, triangular-shaped wire around a circular array of longitudinal rods.

- Slot openings should be continuous around the circumference of the screen, permitting maximum accessibility to the aquifer so that efficient development is possible.
- Slot openings should be spaced to provide maximum open area consistent with strength requirements to take advantage of the aquifer hydraulic conductivity.
- Individual slot openings should be V-shaped and widen inward to reduce clogging of the slots and sized to control sand pumping (see **Figure 5.8**)

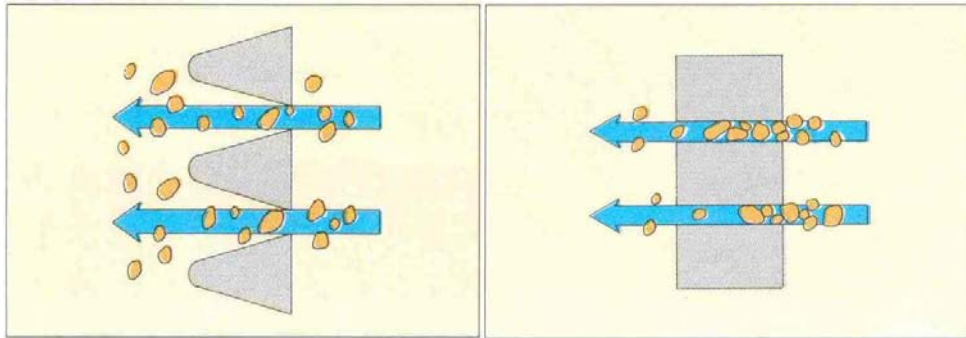


Figure 5.8 V-shaped slot openings reduce clogging where straight cut, punched or gauze-type openings can be clogged by elongate or slightly oversize particles

5.8.1 Screen Slot Types

There are mainly four types of well screen (see **Figure 5.9**), they are:

- ✓ Continuous slot screen
- ✓ Bridge slot screen
- ✓ Louvered screen
- ✓ Slotted pipe

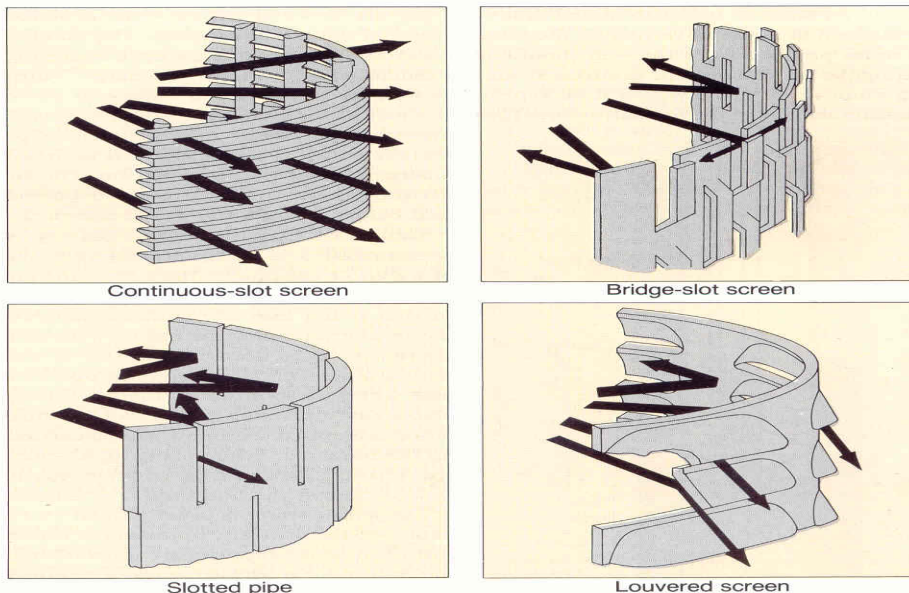


Figure 5.9 Configuration of the slot openings

5.8.2 Screen Slot Size

For naturally developed wells, well-screen slot openings need to be selected from sieve analysis for representative samples from the water-bearing formation. For a homogeneous formation that consists of fine, uniform sand, the size of the screen opening (slot size) is selected as the size that will be pass (50-60) % of the sand (Johnson Division, 1975) i.e. (40-50) % retained. (see **Figure 5.10**)

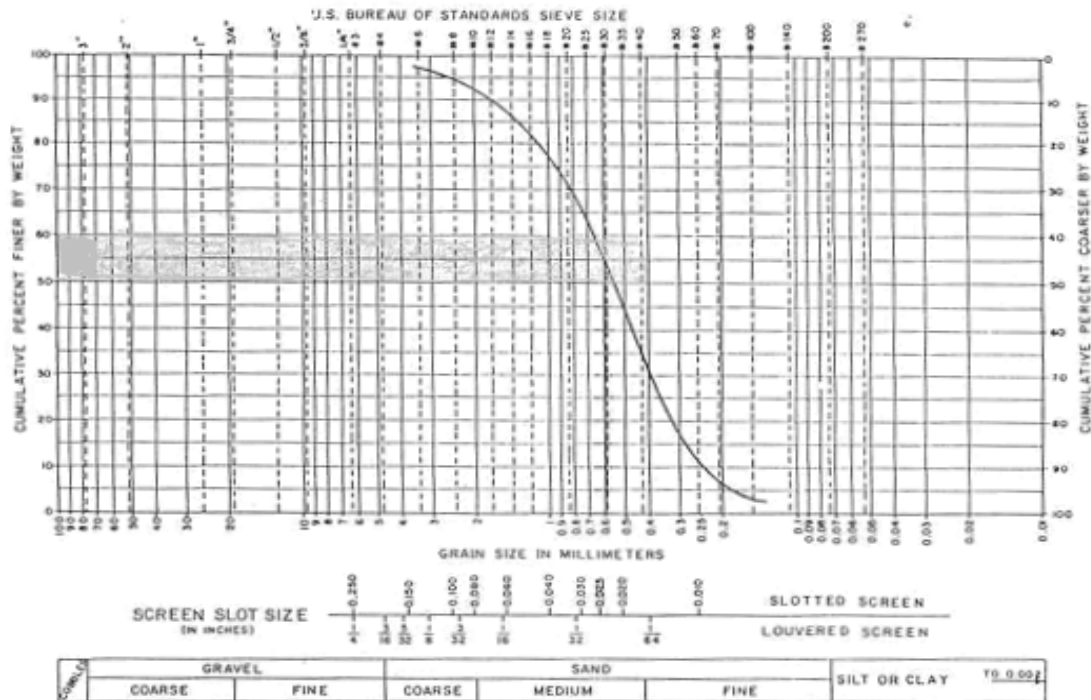


Figure 5.10 Selection of screen slot size for uniform sand

- The 60-percent passing value needs to be used where the ground water is not particularly corrosive, and there is minimal doubt as to the reliability of the sample.
- The 50-percent passing value is used if the water is corrosive or if there is doubt as to the reliability of the sample; the 50-percent passing value is the more conservative design.

In general, a larger slot-size selection enables the development of a thicker zone surrounding the screen, therefore, increasing the specific capacity. In addition, if the water is encrusting, a larger slot size will result in a longer service life. However, the use of a larger slot size may necessitate longer development times to produce a sand-free condition.

A more conservative selection of slot size (for instance, a 50% passing value) is selected if there is uncertainty as to the reliability of the sample; if the aquifer is overlain or underlain by fine-grained, loose materials; or if development time is expensive.

In general, the same sieve-analysis techniques can be used for heterogeneous or stratified aquifers, except as follows:

- If a firm layer overlies the aquifer being evaluated, a slot size that corresponds to a 70% passing value is used.
- If a loose layer overlies the aquifer being evaluated, a slot size that corresponds to a 50% passing value is used.

- If multiple screens are used and if fine-grained material overlies coarse material (**Figure 5.11**):

Extend at least 0.9 m (3ft) of screen that has a slot size designed for the fine material into the coarse section.

The slot size in the coarse material should not be more than double the slot size for the overlying finer material. Doubling of the slot size should be done over screen increments of 2 ft (0.6m) or more.

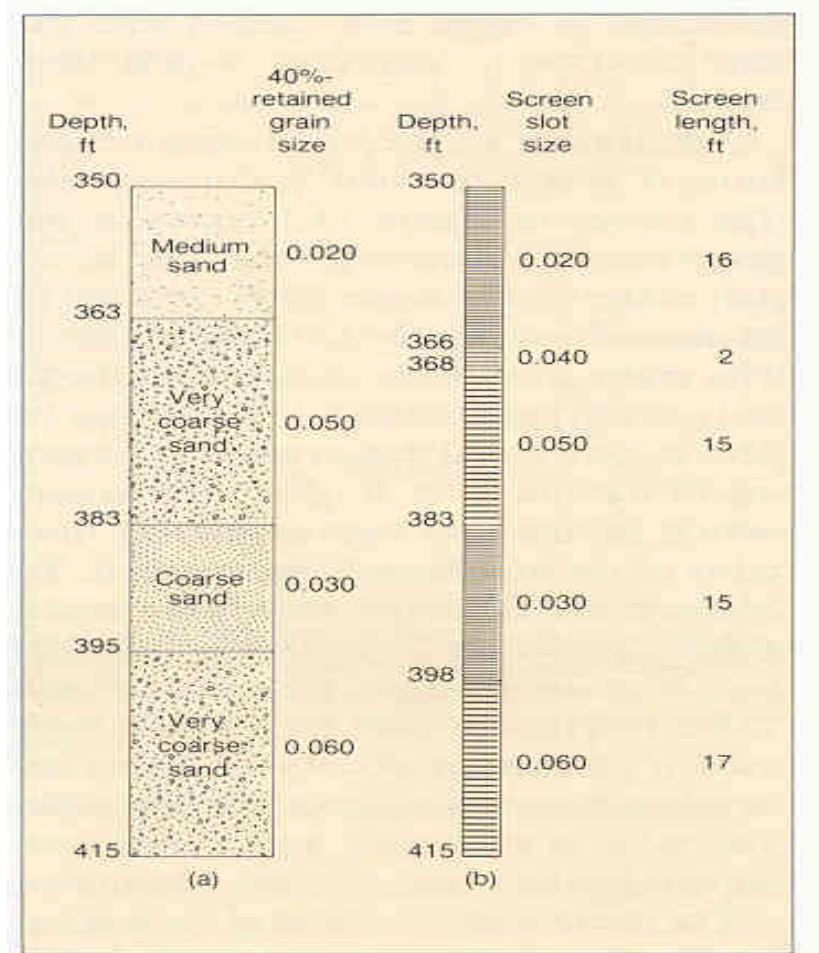


Figure 5.11 (a) Stratigraphic section that will be screened with slot sizes corresponding to various layers. (b) Sketch of screen showing the slot sizes selected on the previous rules (a and b)

5.9 Gravel and Filter Packs

5.9.1 Basic Requirements of Gravel Pack

For formations of fine sands and silts the aquifer must be stabilized. It is not usually practicable to have very small slot sizes, and so an artificial gravel pack is selected which forms the correct size of pore opening, and stabilizes the sand in formation. The use of a pack in a fine formation enables the screen opening to be considerably larger than if the screen were placed in the formation by itself. There is a consequent reduction in head loss. If the grading in the aquifer is small, several gradings in the aquifer is very small, several gradings of gravel pack may be required to retain the formation, and provide practical screen opening sizes.

The gravel pack adjoining the screen consists of larger sized particles than the surrounding formation, and hence larger voids are formed at and close to the screen allowing water entry nearly free from head loss.

Necessary conditions for a gravel pack are:

- ✓ Sand-free operation after development,
- ✓ Highest permeability with stability (low resistance),
- ✓ Low entrance velocities,
- ✓ Efficient service life, i.e. resistant to chemical attack.

5.9.2 Definitions

The following terms are used:

Standard grain size: A particular grain size characteristics of the aquifer (see Module One)

D_x: The sizes of particles such that x percent is smaller, i.e. (100 – x) percent is retained.

Uniformity coefficient: Ratio of the D₆₀ size to D₁₀ size of the material (low coefficient indicates uniform material).

Pack-Aquifer ration (P-A ratio): The ratio of the D₅₀ size of the gravel pack to the D₅₀ size of the aquifer

5.9.3 Natural Gravel Packs

These are produced by the development of the formation itself. Development techniques are used to draw the finer fraction of the unconsolidated aquifer through the screen leaving behind a stable envelope of coarser and therefore more permeable material.

Suitable aquifers are coarse grained and ill sorted, generally with a **uniformity coefficient greater than 3**.

Slot size recommended for the screen is between D₁₀ and D₆₀ (often D₄₀). Choice of slot size is then dependent upon the reliability of the sample and nature of aquifer (e.g. thin and overlain by fine material, formation is well sorted). Not recommended if slot size is less than **0.5 mm**. (see **Figure 5.12**)



Figure 5.12 Natural development removes most particles near the well screen that are smaller than the slot openings, thereby increasing porosity and hydraulic conductivity in a zone surrounding the screen.

5.9.4 Artificial Gravel Pack

Also known as gravel filter pack (see **Figure 5.13**), graded envelope, the gravel pack is intended to fulfill the following functions:

- ✓ To support the aquifer formations and prevent collapse into the casing;
- ✓ To laterally restrain the casing, effectively strengthening the casing;
- ✓ To prevent the movement of fine aquifer material into the well.

The normal approach is to use a filter pack when:

- ✓ The uniformity coefficient < 3 ;
- ✓ The aquifer is fine, with D_{10} of the formation < 0.25 mm.

5.9.5 Gravel Pack Materials

Gravel Pack should be (see **Table 5.2**):

- ✓ Clean.
- ✓ Have well-rounded grains.
- ✓ Free from water soluble compounds such as carbonates (siliceous sands and gravels)
- ✓ Be well graded to insure its function as designed.

Table 5.2 Desirable filter pack characteristics and derived advantages

| Characteristic | Advantage |
|---------------------------------------|--|
| Clean | Little loss of material during development Less development time |
| Well-rounded grains | Higher hydraulic conductivity and porosity Reduced drawdown Higher yield More effective development |
| (90-95)% quartz grains | No loss of volume caused by dissolution of minerals |
| Uniformity coefficient of 2.5 or less | Less separation during installation Lower head loss through filter pack |

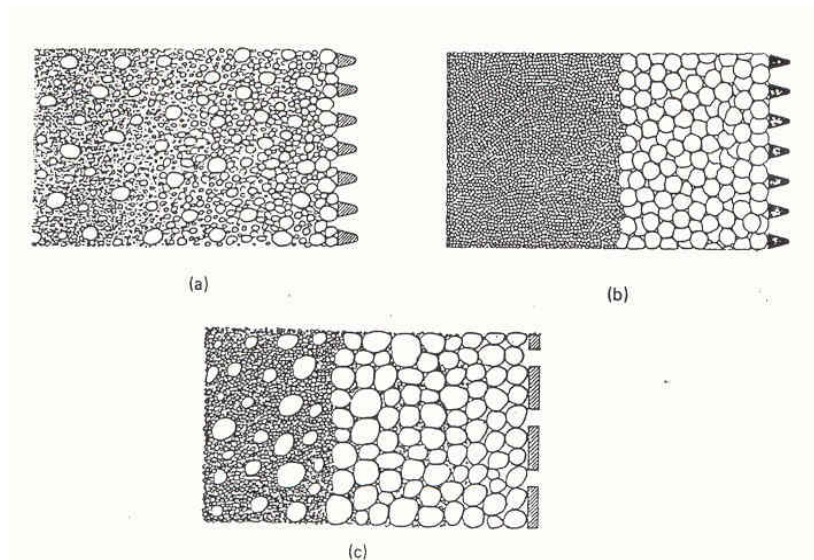


Figure 5.13 The basic differences between the arrangement of the sand and gravel in natural and artificial gravel packed wells. **(a)** The principle of the natural or 'developed' well with each zone correctly graded to the next so that the whole pack is stabilized. **(b)** An artificial gravel packed well in which the correct size relationship is established between the size and thickness of the gravel pack material and the screen slot width. Such a well can be effectively developed and will be efficient and stable. **(c)** Undesirable result of using gravel that is too coarse. The aquifer sand is not stabilized and will eventually migrate into the well. This unstable condition will persist regardless of how thick the gravel pack may be, thus causing a continued threat of sand pumping.

5.9.6 Thickness of Gravel Pack

In theory, a pack thickness of 2 or 3 grains is all that is required to retain formation particles. In practice around 10 cm is used to ensure an envelope around the well. Upper limit of thickness of the gravel pack is 20 cm; otherwise, final well development becomes too difficult and cost of drilling escalates. Packs with a thickness of less than 5 cm are simply formation stabilizers, acting to support the formation, but not effective as a filter.

5.9.7 Selection of Gravel Grading

The aim is to identify the material which will stop significant quantities of material moving into the well while minimizing energy losses. Artificial gravel packs are used where the aquifer material is fine, well-sorted or laminated and heterogeneous. They allow the use of larger slot sizes than would otherwise be possible.

Several methods of determining the gravel pack grain sizes have been suggested. All based initially on a sieve analysis of the aquifer.

The basic rule is (after Terzaghi, 1943):

$$\frac{D_{15 \text{ filter}}}{D_{85 \text{ aquifer}}} < 4 < \frac{D_{15 \text{ filter}}}{D_{15 \text{ aquifer}}} \quad (5.2)$$

A common consensus is that a gravel pack will normally perform well if the uniformity coefficient is similar to that of the aquifer, i.e. the grain size distribution curves of the filter pack and the aquifer material are similar (see **Figure 5.14**). The grain size of the aquifer material should be multiplied by a

constant of approximately (4-7) with average (5) to create an envelope defining the filter grading. (see Figure 5.15)

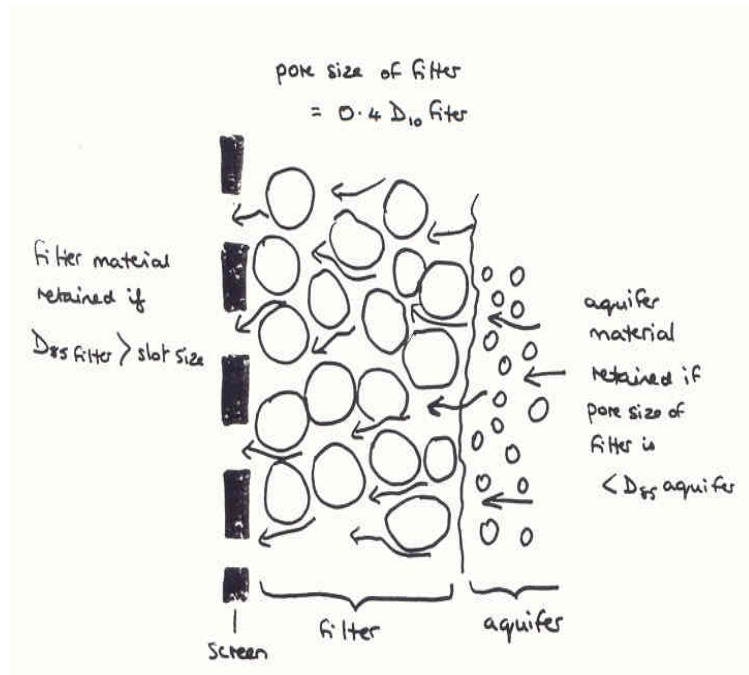


Figure 5.14 Illustration of Terzaghi rule

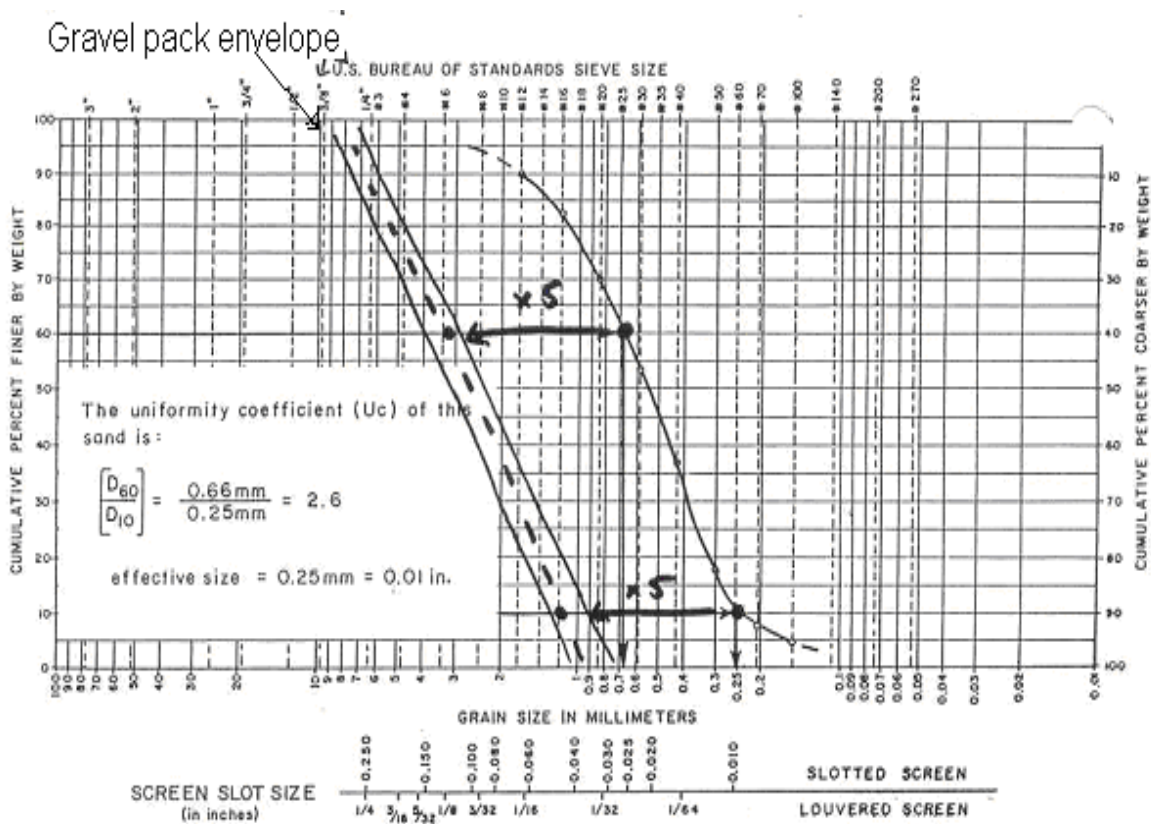


Figure 9.15 Selection of gravel grading

Example 5.1: Well Siting and Well Design

From the details shown on **Figure 5.16** and the data presented in **Table 5.3**,

- a. Determine the areas most suitable for good yielding wells for potable supply.
- b. Suggest a location for a well which is likely to support a minimum of 20 l/s for the drinking water of the town indicated. Using data from nearby wells.
- c. Then for the selected well, suggest likely lithology and depth to bedrock and estimate values of rest water level, surface elevation and specific capacity.
- d. From information found in (c), estimate the long-term drawdown if pumping at 20 l/s. Suggest an appropriate drilling method for this well. Assume that no gravel pack is required, sketch a well design, giving drilled diameter, casing diameter, appropriate pumping size, and screen length.

Table 5.3

| Borehole number | Rest water level elevation (m) | Surface elevation (m) | Depth to bedrock (m) | Lithology (m) | Schedule details | Specific Capacity (l/s/m) |
|-----------------|--------------------------------|-----------------------|----------------------|---|---|---------------------------|
| 1 | 608.7 | 609.2 | 11.1 | 0-11.1 : Silty sands | 8" well, with screen and gravel pack from 8-11 m. Yield 8 l/s | 3.2 |
| 2 | 608.8 | 609.5 | 11.3 | 0-11.3 : Sands with silts and clay | Unused | - |
| 3 | 607.9 | 609.0 | 11.0 | 0-6.8 : Silty sands 6.8-11.0 : Clay and silt | Unused | - |
| 4 | - | 611.6 | 13.9 | 0-13.9 : Well cemented sand and silt | Dry | - |
| 5 | - | 611.7 | 13.5 | 0-13.5 : Well cemented gravel and silt | Dry | - |
| 6 | 603.9 | 607.0 | 9.8 | 0-9.8 : Gravels and sands | 10" slotted pipe 4-9.8 m Contaminated | - |
| 7 | 603.8 | 606.9 | 10.4 | 0-10.4 : Sandy gravel | 10" slotted pipe 4-10.4 m Contaminated | - |
| 8 | 603.7 | 607.0 | 10.8 | 0-10.8 : Gravels and sands | 10" slotted pipe 4-10.8 m Contaminated | 6.8 |
| 9 | 603.7 | 607.0 | 9.6 | 0-9.6 : Sands with silts | 10" slotted pipe 4-9.6 m Contaminated | - |
| 10 | 605.2 | 607.8 | 10.6 | 0 - 10.6 : Sands and silts | 8" slotted pipe gravel packed, 8.8-10 m. Yield 9.5 l/s | 2.4 |
| 11 | 607.8 | 609.1 | 11.1 | 0-11.1 : Sandy silt | Abandoned | - |
| 12 | 607.1 | 608.6 | 11.1 | 0-11.1 : Sand and gravel | 10" slotted pipe gravel 6-10 m. Yield 18 l/s | 6.4 |
| 13 | 606.3 | 608.1 | 11.1 | 0-11.1 : Sand and gravel | 6" screen, unused, screen damaged | - |
| 14 | 606.2 | 608.1 | 11.0 | 0-11.0 : Sandy silt and clay | 8" slotted pipe 5-10 m. pulling fine material | 2.1 |
| 15 | 608.3 | 609.1 | 10.4 | 0-10.4 : Silty sand and clay | Abandoned | - |
| 16 | 609.9 | 609.5 | 11.2 | 0-11.2 : Gravel with sand and silt | 5" slotted pipe 6-10 m. Yield 4 l/s for factory supply | 5.8 |
| 17 | 605.5 | 608.9 | 11.9 | 0-11.9 : Sands with silt and clay | 8" slotted pipe gravel packed, unused | 1.9 |
| 18 | 606.0 | 609.0 | 11.8 | 0-8.6 : Silt and sand 8.6 - 11.8 : Sand and silt | Abandoned | - |
| 19 | 602.2 | 606.5 | 10.5 | 0-10.5 : Silty sand | Old dug well, partially collapsed, contaminated | - |
| 20 | 605.1 | 607.7 | 11.2 | 0-11.2 : Sand and gravel | 8" slotted pipe 5-11 m. Previous 9.5 l/s yield. Contaminated | 5.3 |

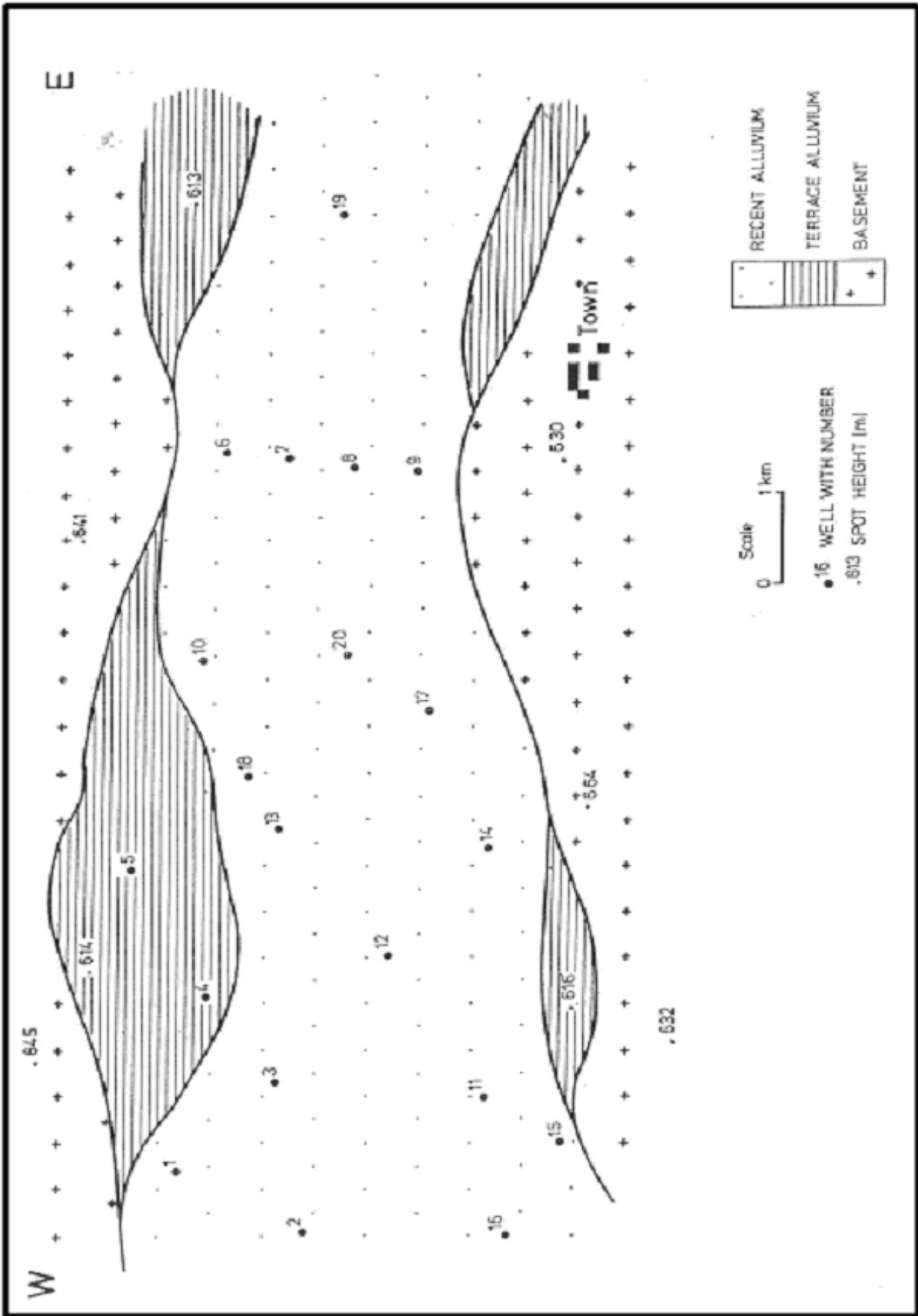
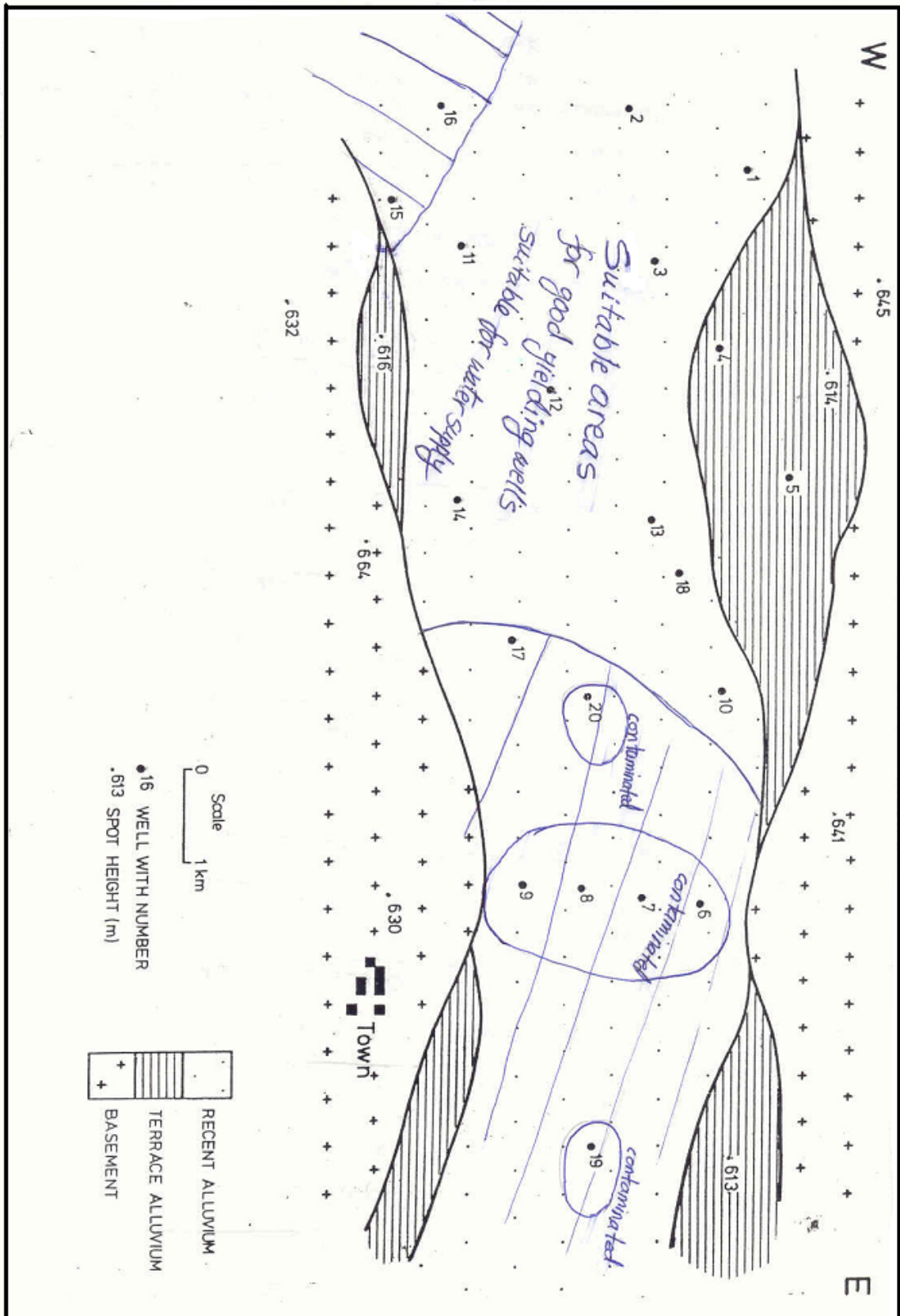


Figure 5.16

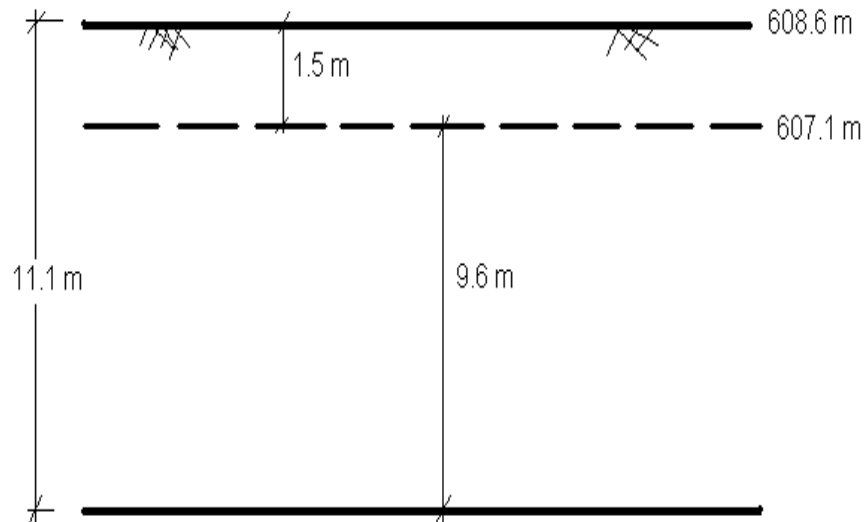
Answer 5.1

- a. The most suitable are for good yielding wells for potable supply is shown in the following figure,



b. The best site is well # 12 because:

- Saturated thickness = 9.6 m.
- Specific capacity = 6.4 l/s/m = 553 m²/day
- The value of specific capacity is high, so $Q \geq 20$ l/s is easily achieved



c. For the selected well,

- Lithology 0 - 11.1 sand and gravel
- Depth to bedrock 11.1 m
- Depth to rest water level 1.5 m
- Surface elevation 608.6 m
- Specific capacity 6.4 l/s/m \approx 553 m²/day

d. For the selected well,

- Long-term drawdown $s_w = 1.22 \frac{Q}{T} \Rightarrow T = 1.22 \frac{Q}{s_w} = 1.22 \times \text{specific capacity}$

$$T = 1.22 \times 553 = 675 \text{ m}^2/\text{day}$$

$$\Rightarrow s_w = 1.22 \frac{Q}{T} = \frac{1.22 \times (20 \times 10^{-3} \times 60 \times 60 \times 24)}{675} = 3.12 \text{ m.}$$

- Appropriate drilling method for this well is power augering, because:

1. The depth is limited only 11.1 m.
2. lithology is loose (sand and gravel)

➤ **Well Design:**

(Screen diameter)

$$Q = V \times A \Rightarrow A = \frac{Q}{V} = \frac{20 \times 10^{-3} \text{ m}^3 / \text{sec}}{1.5 \text{ m/sec}}$$

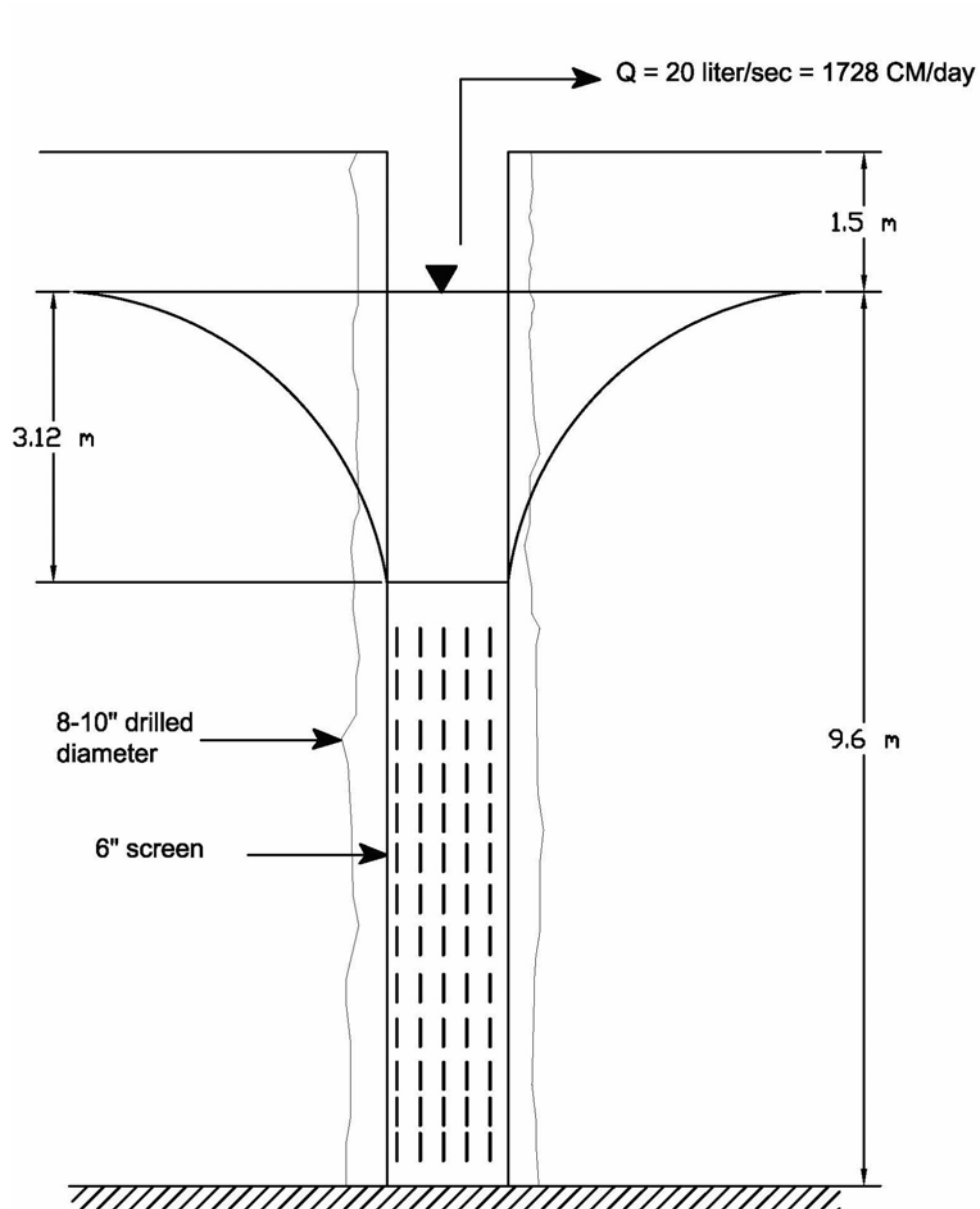
$$\Rightarrow A = 0.0133 \text{ m}^2$$

$$\text{but, } A = \frac{\pi d^2}{4} \Rightarrow d^2 = \frac{4 \times A}{\pi} \Rightarrow d = \sqrt{\frac{4A}{\pi}}$$

$$\Rightarrow d = 0.13 \text{ m}$$

Use 6" screen diameter

(Pump size) - Use 4" diameter



Example 5.2: Gravel Pack Design

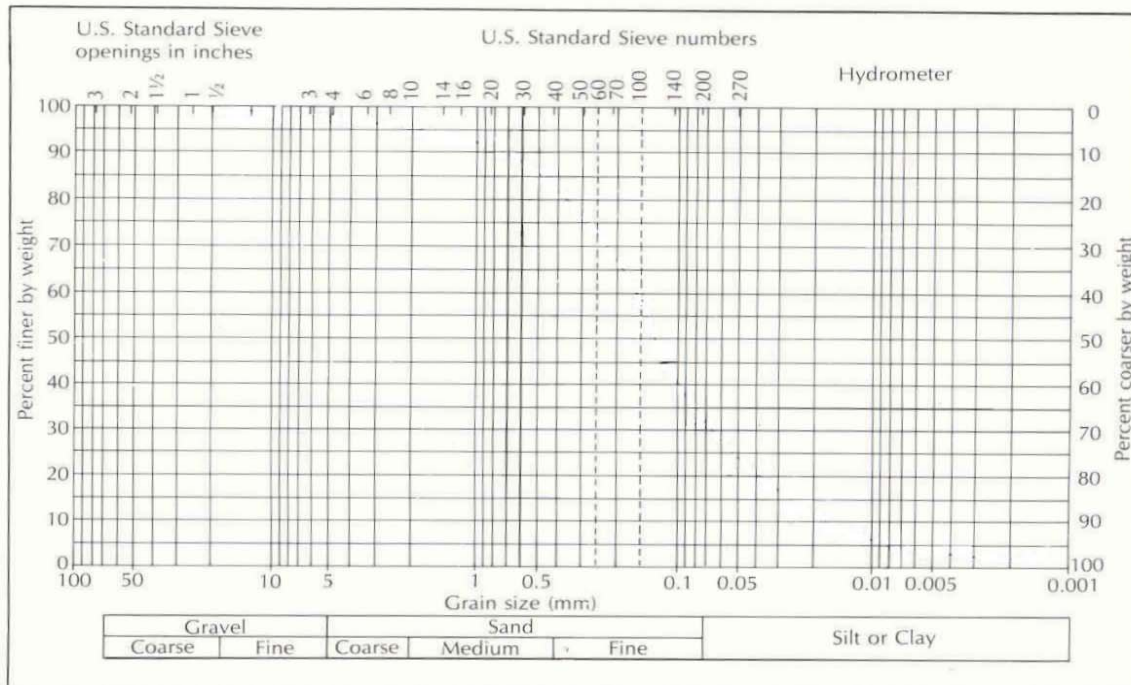
The following table gives the results of a sieve analysis of formation samples taken during drilling of a borehole for water well.

| Sieve size | Mass retained (kg) |
|----------------------------|--------------------|
| 2 | 0 |
| 1 | 0.24 |
| 0.5 | 0.50 |
| 0.25 | 0.78 |
| 0.125 | 0.30 |
| 0.063 | 0.05 |
| Mass passing through 0.063 | 0 |

- Describe the main functions of an artificial gravel pack.
- Construct a grain size distribution curve (Use the attached paper).
- Confirm that an artificial gravel pack is required.
- Construct a grading curve for the gravel pack (Use the same attached paper).
- Suggest a suitable screen slot size.
- What are the main problems that can occur when installing gravel and suggest how they can be kept to a minimum?

Hint

Uniformity coefficient = D_{60} / D_{10}

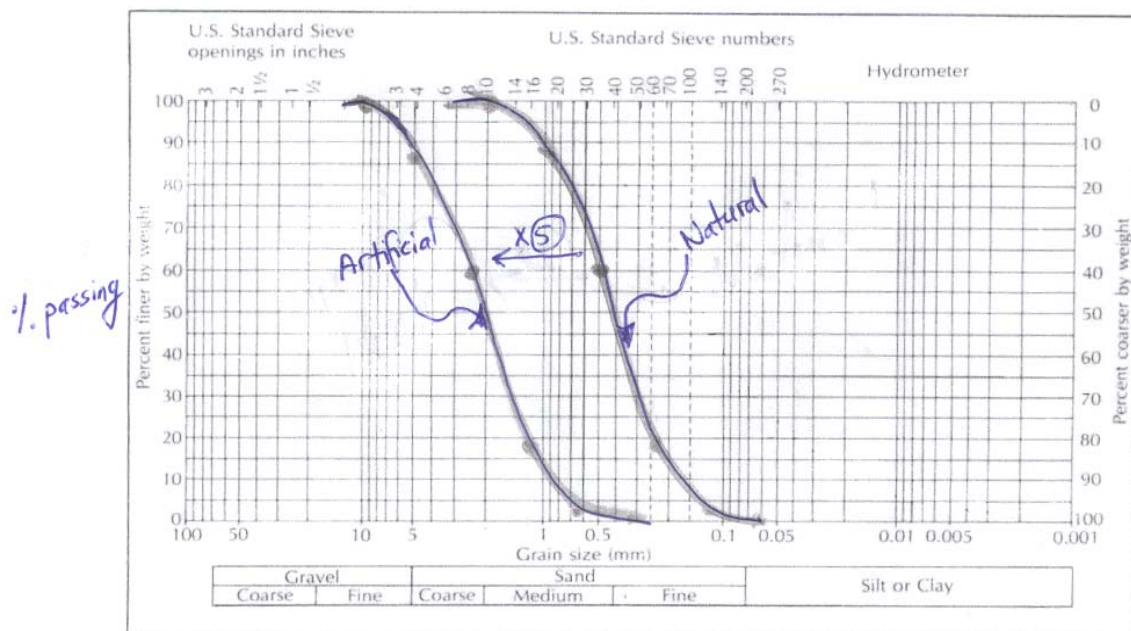


Grain-size distribution curve of a silty fine to medium sand.

Answer 5.2

| Sieve size (mm) (Natural) | Mass retained (kg) | Cumulative mass passing (Kg) | % Passing | Artificial grain size (mm) = natural x 5 |
|-------------------------------|-----------------------|------------------------------------|--------------|---|
| 2 | 0 | 1.87 | 100 | 10 |
| 1 | 0.24 | 1.63 | 87 | 5 |
| 0.5 | 0.50 | 1.13 | 60 | 2.5 |
| 0.25 | 0.78 | 0.35 | 19 | 1.25 |
| 0.125 | 0.30 | 0.05 | 3 | 0.625 |
| 0.063 | 0.05 | 0 | 0 | 0.315 |
| Mass passing through 0.063 | 0 | 0 | 0 | These values are the sizes for gravel pack |
| | Sum = 1.87 kg | | | |

- a. 1. Prevention of fines in well, 2. increase effective hydraulic radius, 3. support formation and prevent collapse leading to damage, 4. laterally restrain and effectively strengthening casing.
- b. the grain size distribution curve is shown below:



Grain-size distribution curve of a silty fine to medium sand.

- c. the artificial gravel pack is required, because:
- ✓ Uniformity Coefficient = $D_{60}/D_{10} = 0.5/0.172 = 2.91 < 3$.
 - ✓ $D_{10} = 0.172 \text{ mm} < 0.25 \text{ mm}$
- d. See the graph above.
- e. Size of screen slot is 85% retained, i.e. 15% pass the gravel pack = **1.3 mm**
- f. Problems and solutions are:

- ✓ **Problems:** segregation and bridging
- ✓ **Solutions:** installation using treimie pipe or reverse circulation

Example 5.3: Gravel Pack Design

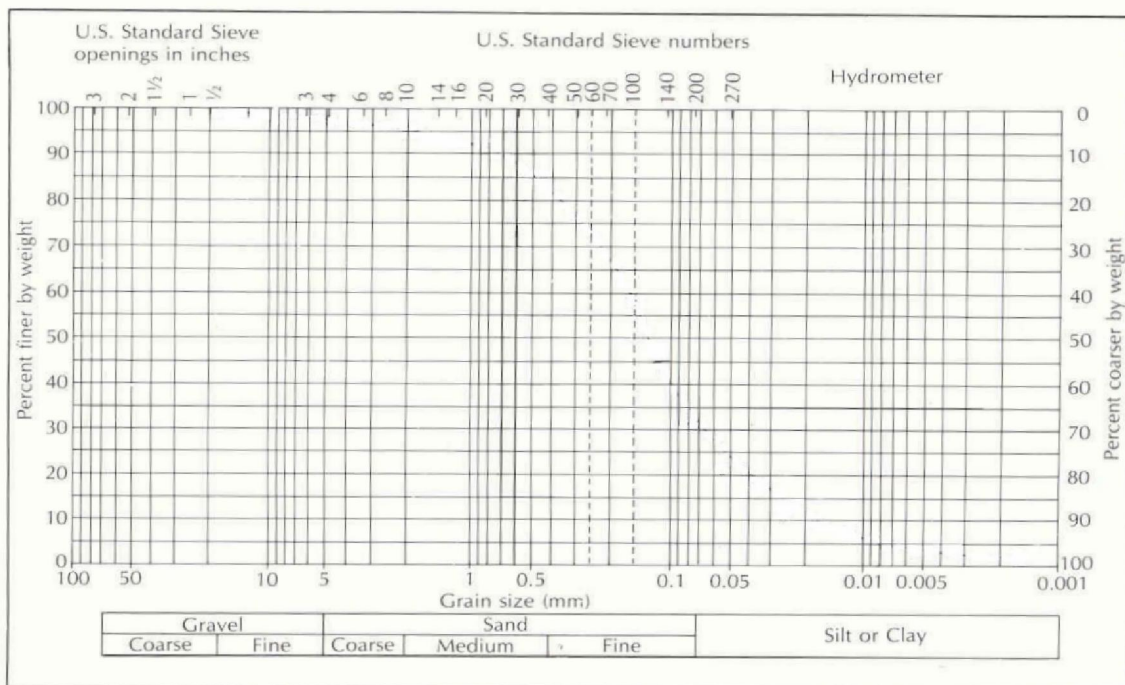
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| Sieve size | Mass retained (kg) |
|----------------------------|--------------------|
| 2 | 0 |
| 1 | 0.24 |
| 0.5 | 0.50 |
| 0.25 | 0.78 |
| 0.125 | 0.30 |
| 0.063 | 0.05 |
| Mass passing through 0.063 | 0 |

- Describe the main functions of an artificial gravel pack
- Construct a grain size distribution curve (Use the attached paper)
- Confirm that an artificial gravel pack is required.
- Construct a grading curve for the gravel pack (Use the same attached paper)
- Suggest a suitable screen slot size
- What are the main problems that can occur when installing a gravel and suggest how they can be kept to a minimum.

Hint

$$\text{Uniformity coefficient} = D_{60} / D_{10}$$

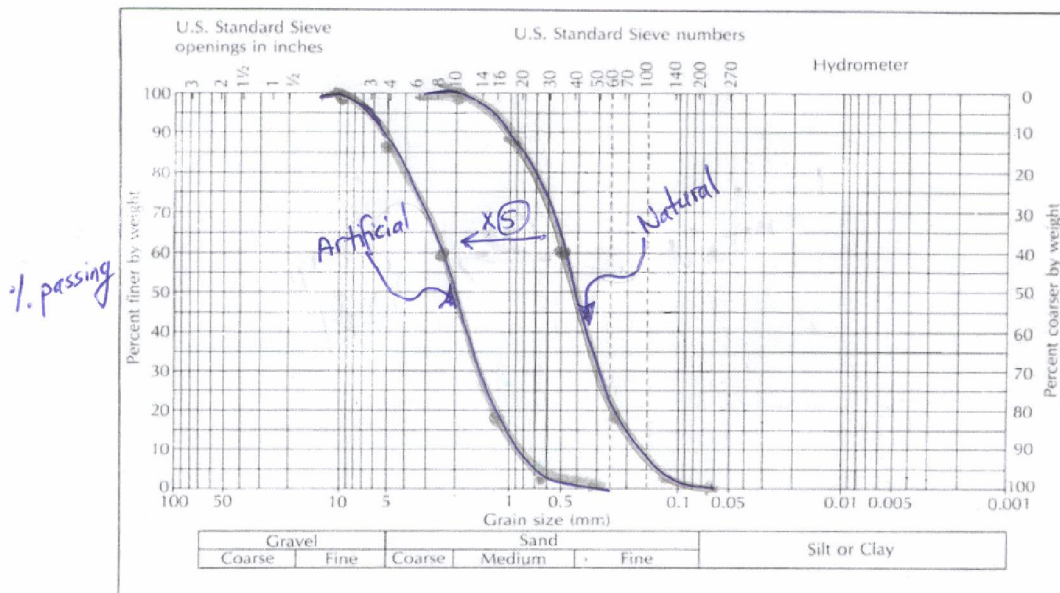


Grain-size distribution curve of a silty fine to medium sand.

Answer for Example 5.3

| Sieve size (mm) (Natural) | Mass retained (kg) | Cumulative mass passing (Kg) | % Passing | Artificial grain size (mm) = natural x 5 |
|-------------------------------|-----------------------|---------------------------------|-----------|---|
| 2 | 0 | 1.87 | 100 | 10 |
| 1 | 0.24 | 1.63 | 87 | 5 |
| 0.5 | 0.50 | 1.13 | 60 | 2.5 |
| 0.25 | 0.78 | 0.35 | 19 | 1.25 |
| 0.125 | 0.30 | 0.05 | 3 | 0.625 |
| 0.063 | 0.05 | 0 | 0 | 0.315 |
| Mass passing through 0.063 | 0 | 0 | 0 | These values are the sizes foravel pack |
| | Sum = 1.87 kg | | | |

- a. 1. Prevention of fines in well, 2. increase effective hydraulic radius, 3. support formation and prevent collapse leading to damage, 4. laterally restrain and effectively strengthening casing.
- b. the grain size distribution curve is shown below:



- c. the artificial gravel pack is required, because:
- ü Uniformity Coefficient = $D_{60} / D_{10} = 0.5 / 0.172 = 2.91 < 3$.
 - ü $D_{10} = 0.172 \text{ mm} < 0.25 \text{ mm}$
- d. See the graph above.
- e. Size of screen slot is 85% retained, i.e. 15% pass the gravel pack = 1.3 mm
- f. Problems and solutions are:
- ü Problems: segregation and bridging
 - ü Solutions: installation using tremie pipe or reverse circulation

Example 5.4: Design of a tube well

Design a tube well assembly to match the strata chart shown in Figure 5.17. The grain-size distribution curve of the aquifer lying between 40 m and 85 m is given in Figure 5.18. The anticipated drawdown is 5 m. The seasonal fluctuation of the water table is 1 m. The hydraulic conductivity is 0.0003216 m/sec and the expected discharge of the well is 0.05 m³/sec.

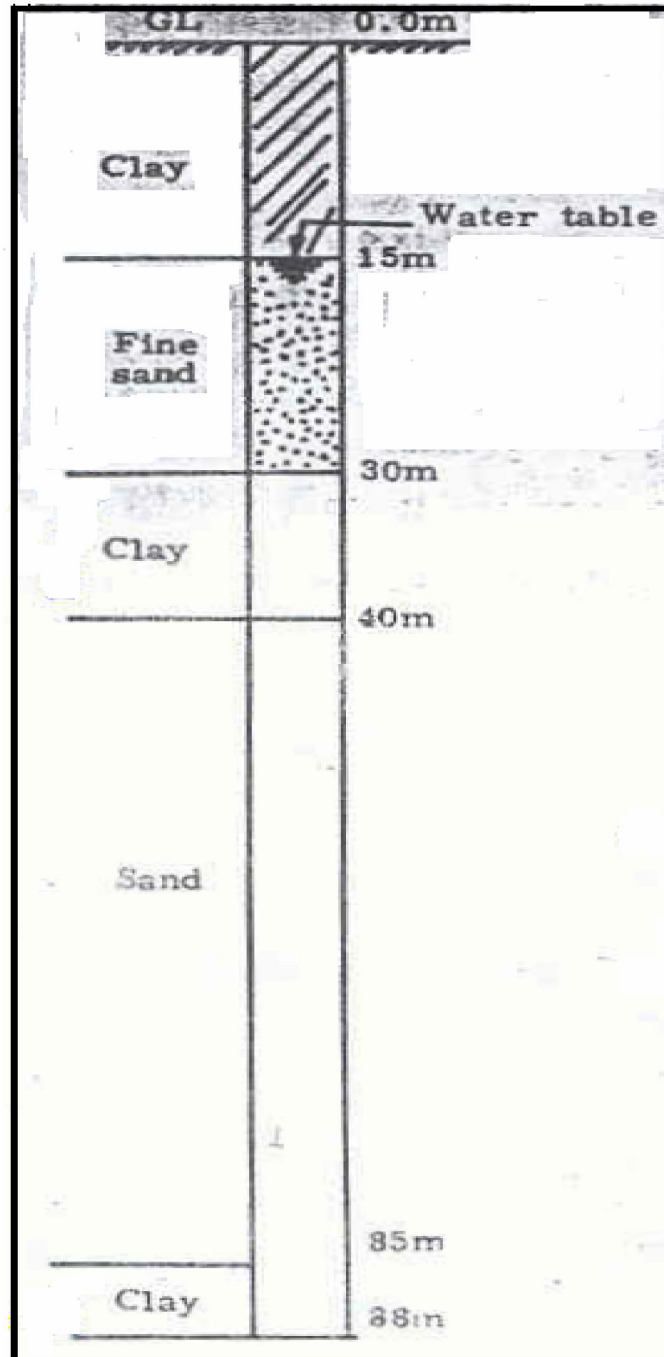


Figure 5.17 Well log

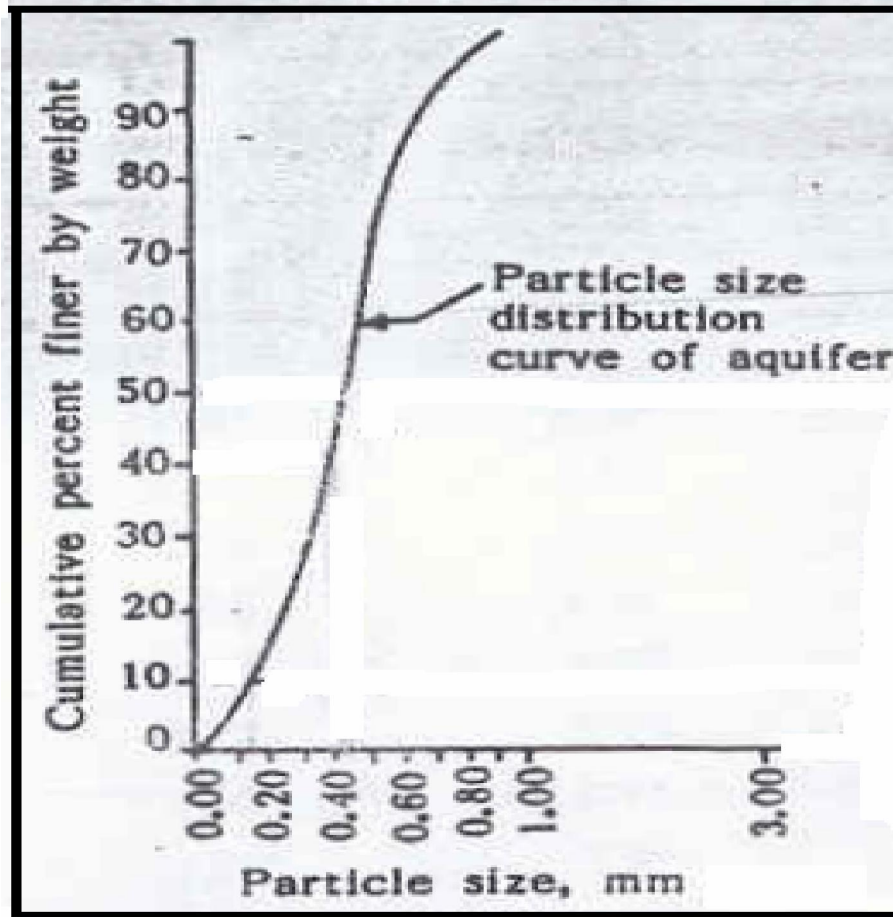


Figure 5.18 grain-size distribution curve of the aquifer

You may use the following tables in the design.

Table 5.4 Diameter and thickness of housing pipes of the tube wells for different sizes of turbines/submersible pumps

| Discharge (l/min) | Nominal diameter of pump (cm) | Diameter of housing pipe (cm) | Thickness of housing pipe (mm) |
|-------------------|-------------------------------|-------------------------------|--------------------------------|
| 475 | 12.5 | 15.0 - 20.0 | 1.5 - 3.5 |
| 1150 | 15.0 | 20.0 - 25.0 | 1.5 - 3.5 |
| 2275 | 20.0 | 25.0 - 30.0 | 2.0 - 3.5 |
| 4550 | 30.0 | 35.0 | 2.0 - 5.0 |
| 7500 | 35.0 | 40.0 | 2.0 - 6.0 |
| 11500 | 40.0 | 45.0 | 2.0 - 6.0 |

Table 5.5 Suggested Thickness of well casing pipe, mm

| Depth of well m | Diameter of well casing, cm | | | | |
|--------------------|-----------------------------|------|------|------|------|
| | 15 | 20 | 25 | 30 | 35 |
| 0 - 10 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 10 - 20 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 20 - 30 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 30 - 40 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 40 - 50 | 1.59 | 1.59 | 1.98 | 1.98 | 2.78 |
| 50 - 60 | 1.59 | 1.98 | 1.98 | 2.78 | 2.78 |
| 60 - 70 | 1.98 | 1.98 | 1.98 | 2.78 | 2.78 |
| 70 - 80 | 1.98 | 1.98 | 1.98 | 2.78 | 3.75 |
| 80 - 90 | 1.98 | 1.98 | 2.78 | 2.78 | 3.75 |
| 90 - 100 | 1.98 | 2.78 | 2.78 | 3.75 | 3.75 |
| 100 - 110 | 1.98 | 2.78 | 3.75 | 3.75 | 3.75 |
| 110 - 120 | 1.98 | 2.78 | 3.75 | 3.75 | 4.76 |
| Above 120 | 2.78 | 3.75 | 3.75 | 4.76 | 4.76 |

Table 5.6 Recommended Diameter of casing pipe and well screen

| Discharge (l/min) | Casing pipe / screen diameter, cm | |
|----------------------|-----------------------------------|-------------|
| | Minimum | Recommended |
| 475 | 10 | 10 |
| 475 - 1125 | 15 | 15 |
| 1125 - 3000 | 20 | 25 |
| 3000 - 5250 | 25 | 30 |
| 5250 - 9500 | 30 | 35 |
| 9500 - 13300 | 35 | 40 |

Hint: $Minimum\ length\ of\ screen = h = \frac{Q_o}{A_o V_o}$,

Where,

- Q_o maximum expected discharge (m^3/min),
- A_o effective open area per meter length of the well screen (m^2),
- V_o entrance velocity at the screen (m/min)

Answer for Example 5.4

1. Design of Housing Pipe

- ü Diameter: The diameter should be large enough to accommodate the pump, with adequate clearance for installation. For a given discharge 3000 l/min (0.05 m³/sec), the nominal diameter of the pump is 30 cm and the recommended diameter of housing pipe is 35 cm. (see Table 5.4).
- ü Thickness of housing pipe: Referring to table 5.4, the thickness of the housing pipe may be taken as 3 mm.
- ü Depth: Depth of housing pipe = Static water level below ground level + drawdown + seasonal fluctuation + allowance for submergence of pump

Assume the allowance for submergence to be 5.5 m.

Assume the clearance between pump and bottom of housing pipe to be 0.5m.

So, the depth of housing pipe = 15 + 5 + 1 + 5.5 + 0.5 = 27 m.

2. Design of Well Casing Pipe

- ü Diameter: Assuming a flow velocity of 1.5 m/sec, for a discharge of 0.05 m³/sec (3000 l/min), the cross-sectional area of the casing pipe,

$$Q = VxA \Rightarrow A = \frac{Q}{V} = \frac{0.05 \text{ m}^3/\text{sec}}{1.5 \text{ m/sec}}$$

$$\Rightarrow A = 0.0333 \text{ m}^2$$

$$\text{but, } A = \frac{\pi d^2}{4} \Rightarrow d^2 = \frac{4xA}{\pi} \Rightarrow d = \sqrt{\frac{4xA}{\pi}}$$

$$\Rightarrow d = 0.206 \text{ m} = 20.6 \text{ cm}$$

However, referring to table 5.6, the minimum diameter of casing pipe for a discharge of 3000 l/min is 20 cm, which is lower than the calculated value. Hence, a plain pipe of 25-cm diameter is selected

- ü Thickness: Referring to table 5.5 for a 25-cm diameter, 87 m deep well, the thickness of a pipe is 2.78 mm.

3. Design of Gravel Pack

The grain size distribution curve of the aquifer material is given in Figure 5.5. The grain sizes d_{10} , d_{50} and d_{60} are 0.13, 0.32, and 0.36 mm, respectively.

The uniformity coefficient is $d_{60}/d_{10} = 0.36/0.13 = 2.8 < 3$ and $d_{10} = 0.13 < 0.25$ mm. it is apparent that the aquifer cannot be developed naturally, and artificial gravel packing has to be provided.

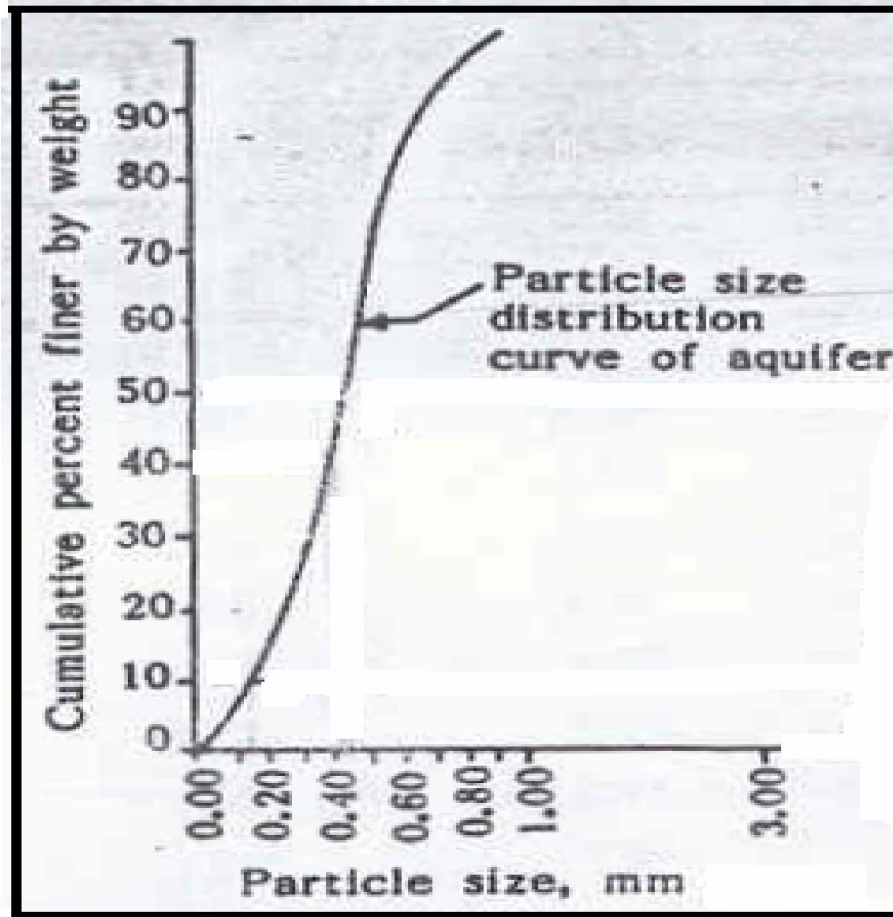


Figure 5.18 grain-size distribution curve of the aquifer

You may use the following tables in the design.

Table 5.4 Diameter and thickness of housing pipes of the tube wells for different sizes of turbines/submersible pumps

| Discharge (l/min) | Nominal diameter of pump (cm) | Diameter of housing pipe (cm) | Thickness of housing pipe (mm) |
|-------------------|-------------------------------|-------------------------------|--------------------------------|
| 475 | 12.5 | 15.0 - 20.0 | 1.5 - 3.5 |
| 1150 | 15.0 | 20.0 - 25.0 | 1.5 - 3.5 |
| 2275 | 20.0 | 25.0 - 30.0 | 2.0 - 3.5 |
| 4550 | 30.0 | 35.0 | 2.0 - 5.0 |
| 7500 | 35.0 | 40.0 | 2.0 - 6.0 |
| 11500 | 40.0 | 45.0 | 2.0 - 6.0 |

- ü Diameter of well screen: The diameter of the well screen is usually kept the same as that of the casing pipe. Hence, it may be kept as 25 cm.
- ü Screen length: The effective area per meter length of the well screen is given by

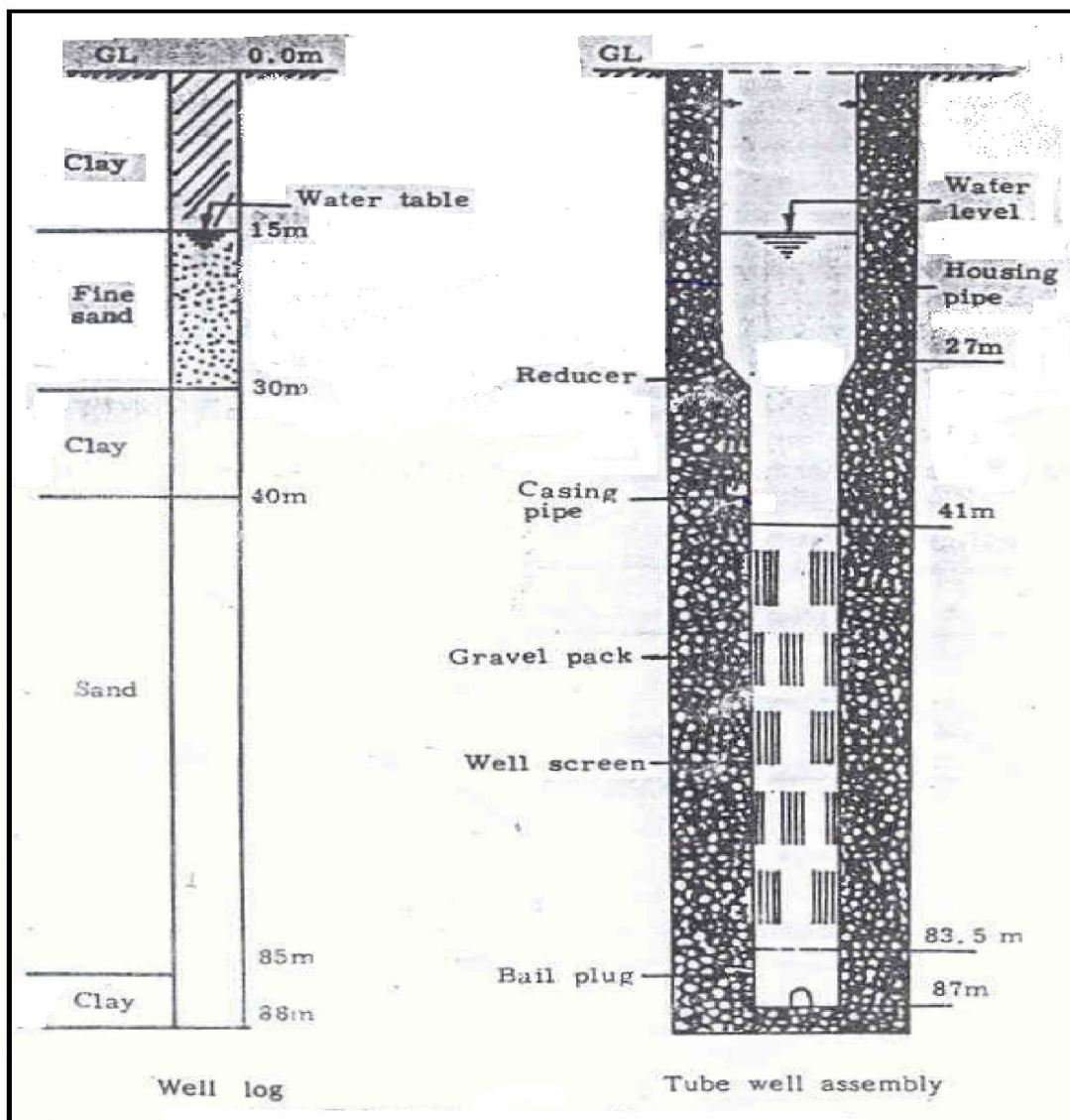
$$A_o = \pi d \times \% \text{ of open area} = \pi \times 0.25 \times 0.1 = 0.078 \text{ m}^2$$

V_o assume to be 1.8 m/min

$$Q_o = 3000 \text{ l/min} = 3 \text{ m}^3/\text{min}$$

$$\text{Then, } h = 3 / (0.078 \times 1.8) = 26.45 \text{ m, say } 27 \text{ m.}$$

The aquifer thickness is 45 m. Therefore, it is desirable to provide about 40 m length of screen, which is more than 27 m and about 90 percent of the aquifer depth. The screen may be provided in the central portion of the aquifer, leaving equal depths untapped at both ends. The design details are illustrated in the following figure.



Tube well pipe assembly to suit well log

ECONOMIC DESIGN OF WELLS



1. Introduction

The cost of water from a well depends upon **the capital invested** and **the annual recurring costs**. A large part of the recurring element derives from the cost of pumping. Capital costs and pumping costs are interdependent to the degree that the design of the well affects the drawdown and thus the pumping cost. For example, a short screen section will produce a larger drawdown than a long screen for a given discharge. Thus saving in capital is offset by increased pumping costs. Similarly a screen of small diameter produces large entry and upflow losses and again increased recurring costs. For each chosen design parameter there is an optimum solution for least cost. This session is concerned with the determination of such least cost solutions.

1. Introduction

The principle of the analysis is to produce an equation representing the total cost in terms of a single design parameter and to apply a discount cash flow procedure to calculate the present value. Differentiation of the present value expression with respect to the chosen parameter leads to the determination of the optimum value of that parameter for minimum cost.



2. Principles of Economic Well Design

In designing wells, the objective is **to produce water for the least cost**. In economic analysis, a distinction is normally made between **economic and financial cost concepts** and the general principles outlined in this session are valid for either approach. The cost of drilling and operating a well comprises the capital investment plus annual recurring costs. A conventional discounting procedure can be applied to these costs and a present value obtained. It is this present value which must be minimized to obtain the optimum well design.



2. Principles of Economic Well Design

Capital and recurring costs of wells are closely interdependent because in a deep aquifer any changes in well screen length, in diameter, or in discharge may affect the drawdown in a well and thus the total head through which the water must be pumped. For example, large diameter well screen and liner may substantially reduce pipe losses. Thus, an increase in capital cost will reduce pumping head and hence pumping costs. Somewhere there is an optimum.



2. Principles of Economic Well Design

The costs of a well can be presented as a functions of the various parameters involved, (see **Figure 2.1**):

$$\text{Capital cost} \quad C = F_1(D, W, \phi, s_w)$$

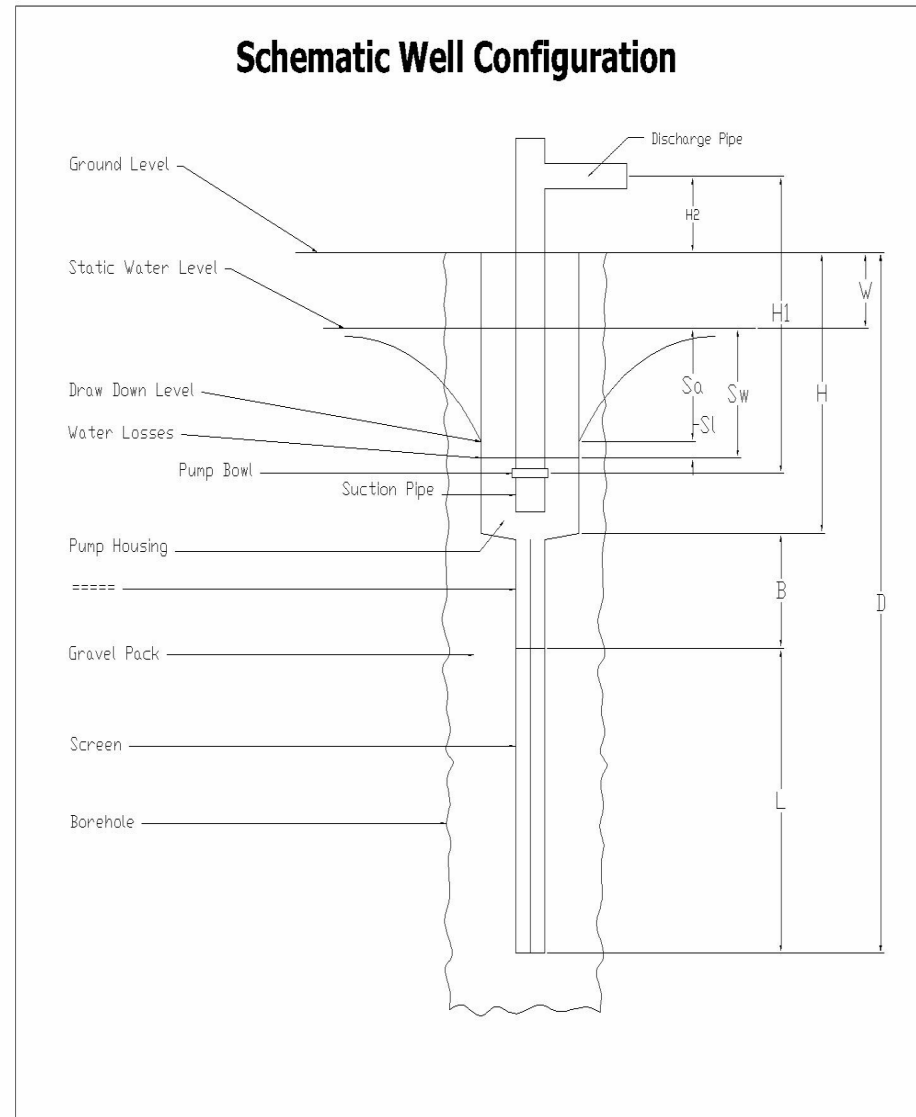
$$\text{Recurring cost} \quad c = F_2(H_2, Q, s_w, m, t)$$

where,

- D** total depth of well
- W** depth of water table or piezometric surface below ground level
- Φ** non-specific diameter
- s_w** drawdown of water level in the well
- H_2** distance between ground level and discharge pipe
- Q** discharge
- m** maintenance cost
- t** hours pumped per year

2. Principles of Economic Well Design

Figure 2.1 Schematic well configuration



2. Principles of Economic Well Design

If c_1, c_2, \dots, c_n represent recurring costs in the years 1 to n , then:

$$\text{Present value } PV = C + c_1 f_1 + c_2 f_2 + \dots + c_n f_n$$

$$f_n = \frac{1}{\left(1 + \frac{r}{100}\right)^n}$$

where,

n is the life of the well in years,
 f_n is the discount factor as shown,
 r is the interest rate percent per annum. Usually values for f are taken from standard tables.

2. Principles of Economic Well Design

By partially differentiating the PV with respect to any of the variables and equating to zero, the optimum value of each variable can be determined for minimum cost.

Thus, $d PV/d L = 0$ would give the optimum screen length for a fixed discharge, diameter, interest rate, and time of pumping. By examining the various partial differentials in turn the well design can be optimized.



3. Inter-relationships Between The Variables

Solutions to the equations depend upon the relationships between Q , s_w , d (diameter of flow conduit "pipe or casing") and L (length of screen). These relationships are entirely empirical and have been derived from a large number of well tests.

For a uniform aquifer, which is deep compared with all likely screen length. The drawdown in the well (s_w) is the same as the drawdown in the aquifer (s_a), for wells of zero well losses, and at equilibrium:

$$s_w = \frac{AQ}{KL}$$

3. Inter-relationships Between The Variables

To account for the well loss (s_w), the relationship derived by Rorabaugh (1953) gives:

$$s_w = BQ + CQ^n$$

or

$$s_w = s_a + s_l$$

in these equations, **A**, **B**, and **C** are constants and **K** is the hydraulic conductivity of the aquifer. Well losses are presented by the term **CQⁿ** and can be broken down further into screen entrance losses and pipe losses in the well.

For most practical cases of wells correctly designed, entrance losses should be negligible and may be disregarded.

3. Inter-relationships Between The Variables

The manner in which costs relate to the variable parameters is not easy to obtain.

For example, while it is fairly easy to abstract well costs from a contractor's tender, it is more difficult to determine just how these costs might change if the diameter of the well was increased; heavier equipment might be required than that assumed in pricing an existing tender.

Similarly, to obtain a complete matrix of pump price variations with different discharges, pump settings, and total delivery heads is more than many manufacturers are willing to provide.

4. Calculation Of The Present Value (PV)

To calculate PV, one should follow the following procedures:

1. It is necessary to reduce the number of variables in the capital cost.

$$s_w = \frac{1.25 Q}{KL}$$

The dimensional relationships used in the simplification may be derived from **Figure 2.1** and are for a particular case:

$$H_1 = W + H_2 + 1.25s_w$$

$$H = H_1 - H_2 + 3.6$$

$$D = H + B + L$$

4. Calculation Of The Present Value (PV)

These allow for:

- ✓ the mean drawdown throughout the well's life to be 25% greater than the initial value,
 - ✓ a pump housing length **H** to induce an extra **3.6 m (12 ft)** below the pump bowl, **3 m (10 ft)** for the length of suction pipe and **0.61 m (2 ft)** for the end clearance.
2. The capital cost must be derived from the collected and estimated data.
 3. The recurring costs "running costs" must be derived from the collected and estimated data.

4. Calculation Of The Present Value (PV)

4. Note, when the running cost is the same every year, it can be discounted to present value by using a single factor which is dependent on the life of the project and the discount rate adopted. **For example**, if a life of 20 years is used and an interest rate of 10%, then the **discount factor** is **$f = 8.5136$** , and the present value of the total cost is **$PV = C + 8.5136c$** . since,

$$\text{Running cost} = c_1 f_1 + c_2 f_2 + \dots + c_n f_n$$

$$\text{but in this case } c_1 = c_2 = \dots = c_n$$

$$\text{so, running cost} = c(f_1 + f_2 + \dots + f_n) = c f$$

$$f_n = \frac{1}{\left(1 + \frac{r}{100}\right)^n}$$

And, $f_1 = 1/1.1^1 = 0.909$, $f_2 = 1/1.1^2 = 0.826$, $f_3 = 1/1.1^3 = 0.751$,
 $f_4 = 0.683$, ... , $f_{20} = 1/1.1^{20} = 0.147$.

So, **discount factor (f)** = $f_1 + f_2 + \dots + f_{20} = 8.5136$

4. Calculation Of The Present Value (PV)

5. Now, the total cost can be determined, which is the sum of capital costs and running costs.

Present value $PV = C + c_1 f_1 + c_2 f_2 + \dots + c_n f_n$

5. Optimum Screen Length

For minimum present value, the partial differential of present value with respect to screen length must equal to zero (see **Figure 4.1**):

$$dPV/dL = 0$$

The method outlined above only gives the optimum for minimum overall cost, but it is interesting to examine the nature of that minimum and to test the sensitivity of the result to changes in the assumptions.



6. Optimum Discharge

By a similar process to that illustrated previously, the optimum discharge can be determined from the present value equation. But because the least cost in terms of Q occurs when the well is not pumped at all, it is necessary to consider the problem in terms of least cost of water per unit of discharge. Thus dividing the present value by the well capacity, as shown below:

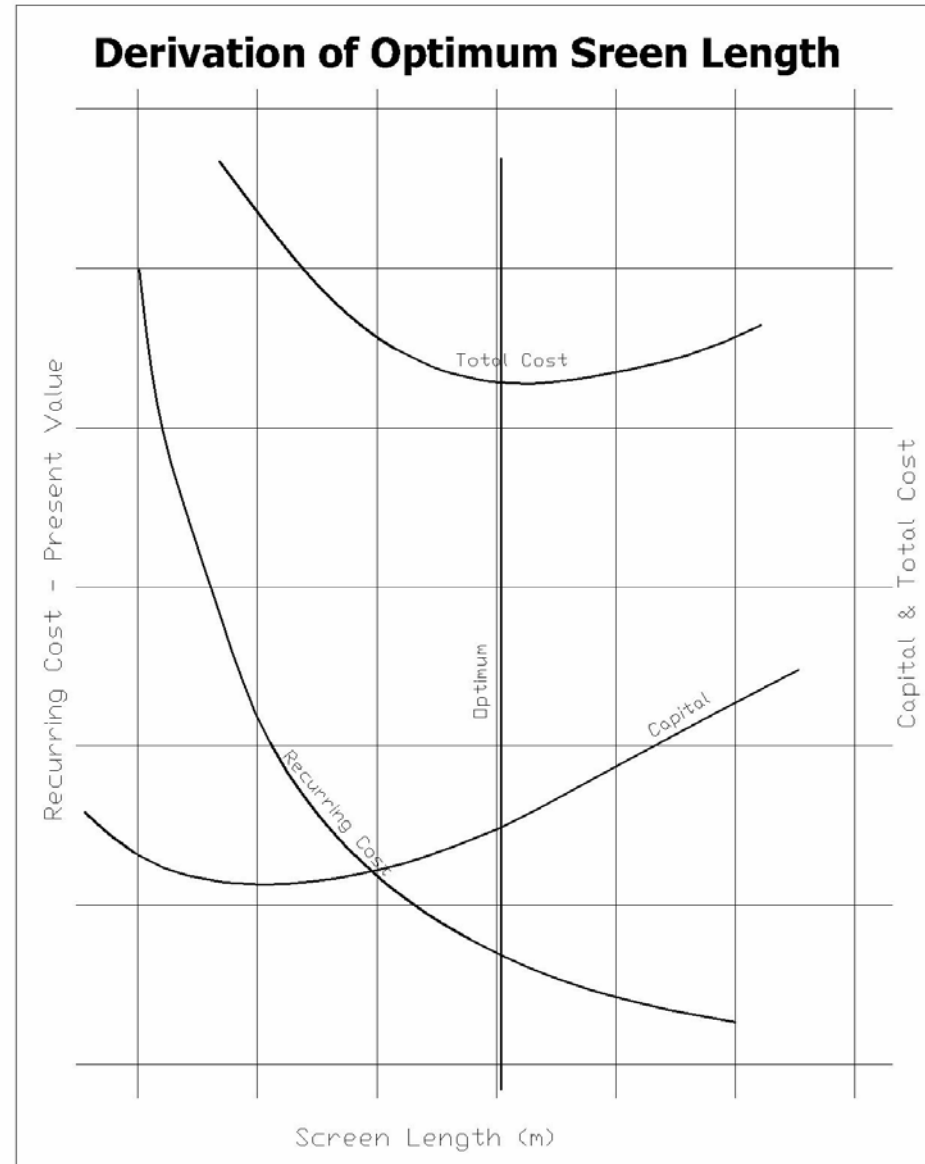
$$V = \frac{PV}{Q}$$

then ,

$$\frac{dV}{dQ} = 0$$

4. Calculation Of The Present Value (PV)

Figure 4.1 Derivation of optimum screen length



Example 5.5: Economic Design of Well

The following information relates to a well in an extensive aquifer:

| | | |
|----------------|---|---|
| AQUIFER: | Unconfined | |
| | Maximum depth to static water | 10 m |
| | Hydraulic conductivity | 40 m/day |
| PUMP: | | |
| | Discharge | 3000 m ³ /day |
| | Recommended submergence (from operating water level in well to clearance below lowest part of pump) | 2.5 m |
| | Discharge delivery head (above ground level) | 1.0 m |
| WELL DRAWDOWN: | | |
| | Drawdown given by | $S = \frac{1.3Q}{KL}$ |
| | Factor of safety against deterioration in specific capacity | 25% |
| | Screen upflow losses (in metre-day units) | $2.0 \times 10^{-15} Q^2 L_r^{-16/3} m$ |
| COSTS: | | |
| | Drilling and other related length costs | \$240/day |
| | Upper well casing | \$130/day |
| | Screen: 200 mm diameter | \$200/day |
| | 150 mm diameter | \$165/day |
| | Fixed costs | \$20000 |
| | Pumping costs (Q in m ³ d ⁻¹ and H in m) | \$0.16QH/year |
| | Discount factor | 8.0 |

Determine the screen diameter and length which gives the minimum cost well.

Note: You may assume that there are no geological constraints on screen length or position. Screen is supplied in lengths which are multiples of a meter.

Answer for Example 5.5

For 200 mm diameter screen

CAPITAL COST

Fixed Capital cost = 20,000

Variable Capital Cost

$$\begin{aligned} \text{Drilling and other related costs} &= 240 [10 \text{ 'depth to static level' } + 2.5 \text{ 'recommended} \\ &\quad \text{submergence' } + \text{total } s_w + L \text{ 'screen length' }] \\ &= 240 [12.5 + \text{total } s_w + L] \end{aligned}$$

$$\text{Upper well casing} = 130 [12.5 + \text{total } s_w]$$

$$\text{Screen} = 200 L$$

$$\text{Total variable capital costs (C)} = 4,625 + 370 \text{ total } s_w + 440 L$$

$$\text{but, Total drawdown} = 1.25 \times [\text{drawdown of aquifer "s}_w\text{" } + \text{screen upflow losses}]$$

$$= 1.25 \times \left[\frac{1.3Q}{KL} + 2.0 \times 10^{-15} Q^2 L r_w^{-16/3} \right]$$

$$= 1.25 \times \left[\frac{1.3 \times 3000}{40 \times L} + 2.0 \times 10^{-15} \times 3000^2 L \times 0.1^{-16/3} \right]$$

$$= 1.25 \times \left[\frac{97.5}{L} + 3.878 \times 10^{-3} L \right]$$

$$= \frac{121.88}{L} + 4.848 \times 10^{-3} L$$

$$\text{So, total variable capital costs} = 4,625 + 370 \left[\frac{121.88}{L} + 4.848 \times 10^{-3} L \right] + 440 L$$

$$= 4,625 + 441.8 L + \frac{45,095.6}{L}$$

$$\text{TOTAL CAPITAL COST} = 24,625 + 441.8 L + \frac{45,095.6}{L}$$

OPERATING COSTS

$$c = 0.16QH, \text{ where } H = 10 + 1 + 2.5 + 1.25 \text{ total } s_w = [13.5 + 1.25 \text{ total } s_w]$$

$$c = 0.16 \times 3000 \times [13.5 + 1.25 \times (\frac{121.88}{L} + 4.848 \times 10^{-3} L)]$$

$$= 6,480 + \frac{73,128}{L} + 2.9 L$$

$$PV = cf = [6,480 + \frac{73,128}{L} + 2.9 L] \times 8 = 51,840 + \frac{585,024}{L} + 23.2 L$$

$$\text{Total PV} = [24,625 + 441.8 L + \frac{45,095.6}{L}] + [51,840 + \frac{585,024}{L} + 23.2 L]$$

$$= 76,465 + 465 L + \frac{630,119.6}{L}$$

$$\frac{dPV}{dL} = 465 - \frac{630,119.6}{L^2}$$

$$\text{For minimum cost } \frac{dPV}{dL} = 0$$

$$L^2 = \frac{630,119.6}{465} = 1355.1$$

$$L = 36.8 \text{ m}$$

$$\text{Cost} = 76,465 + 465 \times 36.8 + \frac{630,119.6}{36.8}$$

$$= \text{US \$ } 110,700$$

For 150 mm diameter screen

CAPITAL COST

Fixed Capital cost = 20,000

Variable Capital Cost

$$\begin{aligned}\text{Drilling and other related costs} &= 240 [12.5 + \text{total } s_w + L] \\ \text{Upper well casing} &= 130 [12.5 + \text{total } s_w] \\ \text{Screen} &= 165 L \\ \text{Total variable capital costs (C)} &= 4,625 + 370 \text{ total } s_w + 405 L\end{aligned}$$

$$\begin{aligned}\text{but, Total drawdown} &= 1.25 \times [\text{drawdown of aquifer "s}_w\text{" + screen upflow losses}] \\ &= 1.25 \times \left[\frac{1.3Q}{KL} + 2.0 \times 10^{-15} Q^2 L r_w^{-16/3} \right] \\ &= 1.25 \times \left[\frac{1.3 \times 3000}{40 \times L} + 2.0 \times 10^{-15} 3000^2 L \times 0.075^{-16/3} \right] \\ &= 1.25 \times \left[\frac{97.5}{L} + 1.799 \times 10^{-2} L \right] \\ &= \frac{121.88}{L} + 2.248 \times 10^{-2} L\end{aligned}$$

$$\begin{aligned}\text{So, total variable capital costs} &= 4,625 + 370 \left[\frac{121.88}{L} + 2.248 \times 10^{-2} L \right] + 405 L \\ &= 4,625 + 413.32 L + \frac{45,095.6}{L}\end{aligned}$$

$$\text{TOTAL CAPITAL COST} = 24,625 + 413.32 L + \frac{45,095.6}{L}$$

OPERATING COSTS

$$c = 0.16 \times 3000 \times \left[13.5 + 1.25 \times \left(\frac{121.88}{L} + 2.248 \times 10^{-2} L \right) \right] = 6,480 + \frac{73,128}{L} + 16.86 L$$

$$\text{PV} = \text{cf} = \left[6,480 + \frac{73,128}{L} + 16.86 L \right] \times 8 = 51,840 + \frac{585,024}{L} + 134.88 L$$

$$\begin{aligned} \text{Total PV} &= [24,625 + 413.32 L + \frac{45,095.6}{L}] + [51,840 + \frac{585,024}{L} + 134.88 L] \\ &= 76,465 + 548.2 L + \frac{630,119.6}{L} \end{aligned}$$

$$\frac{dPV}{dL} = 548.2 - \frac{630,119.6}{L^2}$$

$$\text{For minimum cost } \frac{dPV}{dL} = 0$$

$$L^2 = \frac{630,119.6}{548.2} = 1,149.43$$

$$L = 33.9 \text{ m}$$

$$\begin{aligned} \text{Cost} &= 76,465 + 548.2 \times 33.9 + \frac{630,119.6}{33.9} \\ &= \text{US\$ } 113,637 \end{aligned}$$

So, the cheapest option is to use 37 m of 200 mm screen

Example 5.6: Economic Design of Well

You have been asked to produce a least cost design for a new well penetrating a confined aquifer. Given the following cost information and design data, determine the optimal single string well design.

AQUIFER DATA

| | |
|----------------------------------|-----------|
| Top of aquifer | 25 m/bgl |
| Base of aquifer | 80 m/bgl |
| Average Piezometric Surface | 10 m/bgl |
| Yearly Fluctuation | +/- 1.0 m |
| Long term yearly av. Fluctuation | +/- 4.0 m |
| Long term drawdown | 6.0 m |
| Average Hydraulic Conductivity | 20 m/day |

WELL MATERIAL COST

| | |
|---------------------|---------|
| Pump Chamber Casing | \$ 50/m |
| Well Screen | \$ 80/m |
| Drilling | \$ 35/m |
| Reducer | \$ 175 |
| Bail Foot | \$ 60 |
| Gravel Pack | \$ 20/m |
| Pump Installation | \$ 2500 |

OPERATING COSTS

$$c = 1.58 \times 10^{-4} \times Q.H.t$$

where, Q = discharge m³/day

H = water lift (m)

t = time in days

DESIGN CONSIDERATION

| | |
|--|--------------------|
| Well Life | 20 years |
| Pump Replacement | every 8 years |
| Well Deterioration | 1%/ year |
| (i.e. an increase in the drawdown in the well of 1% each year) | |
| Pump sitting | 1 m |
| Well losses | 0.1 s _w |
| Safety against deterioration | 3 m |

EQUATIONS

| | |
|-------------------|--|
| Drawdown given by | $S_w = \frac{1.3Q}{KL}$ |
| Present Value | $NPV(A) = \frac{A[(1+r)^n - 1]}{r(1+r)^{n-1}}$ |

Where, A: annuity, r: interest rate, n: number of years.

HINT

Formulate all the equations in terms of Q and L, then find the least cost and the optimal screen length when Q was 10, 20, and 30 l/s

Answer for Example 5.6

ü CAPITAL COST

- (i) Pump chamber casing (PC)

Pump chamber length= 10 (average piezometric surface) + 4 (long term fluctuation) + 1 (yearly fluctuation) + 6 (long term drawdown) + 1 (pump sitting) + 3 (safety) + s_w (drawdown) + 20% s_w (1% an increase in the drawdown for each year) +10% s_w (10% of the drawdown for the well losses).

$$PCL = 10+4+1+6+1+3+s_w+0.2s_w+0.1s_w$$

$$PCL = 25 + 1.3 s_w$$

$$\text{But, } S_w = \frac{1.22Q}{KL}$$

$$\text{Then P.C.L} = 25 + \frac{1.59Q}{20L_s} = 25 + \frac{0.0793Q}{20L_s}$$

Assume that the peak discharge is 10 l/sec = 864 m³/day.

$$\text{Then, P.C.L} = 25 + \frac{68.5}{L_s}$$

$$\text{But, cost of P.C} = \$ 50/\text{m} = 50 \left[25 + \frac{68.5}{L_s} \right] = 1250 + 3425/L_s$$

So,

| | L_s (m) | Cost of the pump chamber length (\$) |
|---|-----------|--------------------------------------|
| ü | 10 | 1592.5 |
| ü | 20 | 1421.25 |
| ü | 30 | 1346.17 |
| ü | 40 | 1335.6 |
| ü | 50 | 1318.5 |

- (ii) Well screen (L_s) = cost of well screen = 80 L_s

- (iii) Drilling length = L_s +PCL+ length of reducer + Length of bail foot

$$= L_s + 25 + \frac{68.5}{L_s} + 1 + 2$$

$$= 28 + L_s + \frac{68.5}{L_s}$$

$$\text{Cost of drilling} = 25 \left[28 + L_s + \frac{68.5}{L_s} \right]$$

$$= 980 + 35 L_s + 2397.5 / L_s$$

- (iv) Cost of Bail foot = \$ 60
 (v) Cost of Reducer = \$ 175
 (vi) Gravel Pack

The pack will cover the length of the screen + extra length for operating + length of reducer + length of bail foot.

$$\begin{aligned} \text{Length of gravel pack} &= L_s + (4 \text{ extra}) + 1 + 2 \\ &= L_s + 7 \end{aligned}$$

$$\text{Cost of gravel Pack} = 20 [L_s + 7] = 20 L_s + 140$$

So, the Capital Costs = cost of pump chamber length + cost of well screen length + cost of drilling + cost of bail foot + cost of reducer + cost of gravel pack

$$= 1250 + 3425/L_s + 80 L_s + 980 + 35 L_s + 2397.5 / L_s + 60 + 175 + 20 L_s + 140$$

$$\text{Capital cost} = 2605 + 135 L_s + 5822.5/L_s$$

| L_s (m) | Capital Costs (\$) |
|-----------|--------------------|
| 10 | 4537.25 |
| 20 | 5596.13 |
| 30 | 6849.1 |
| 40 | 8150.5 |
| 50 | 9471.5 |

ü RUNNING COST

$$R_c = 1.58 \times 10^{-4} \times Q \cdot H \cdot t$$

$$Q = 864 \text{ m}^3/\text{day}$$

t = here we assume that the operating is 24 hours/day, so t= 365 day

$$\begin{aligned} H &= \text{water lift} = \text{Distance above the ground level we want to lift the water to it} + \\ &\quad \text{water table below ground level} + \text{drawdown} + \text{well losses (0.1 } s_w) \\ &= 1 + 10 + s_w + 0.1 s_w = H \end{aligned}$$

but we know that the drawdown is fluctuated along the life of the well so we take the average of that = $(0.1+0.2)s_w/2 = 0.105 s_w$

$$\text{Finally, } H = 11 + 1.1 s_w + 0.105 s_w = 11 + 1.205 s_w$$

$$\text{But, } s_w = \frac{1.22Q}{KL} = 1.22 \times 864 / 20L_s = 52.704 / L_s$$

$$\text{Then, } H = 11 + 63.51/L_s$$

$$\text{So, } R_c = 1.58 \times 10^{-4} \times 864 \times [11 + 63.51/L_s] \times 365$$

$$R_c = 548 + 3164.5/L_s$$

So, we need to calculate the Net Present Value (NPV) of Running cost (Rc)

$$NPV(A) = \frac{A[(1+r)^n - 1]}{r(1+r)^{n-1}} = [548 + 3164.5/L_s] \times \frac{1.1^{20} - 1}{(0.1)(1.1)^{19}}$$

$$NPV_1 = [5132 + 29635/L_s]$$

Then, for installation after 8 years $NPV_2 = 2500 \times \frac{1}{(1+0.1)^8} = 1166$

For installation after 8 years $NPV_3 = 2500 \times \frac{1}{(1+0.1)^{16}} = 544$

Running Costs = $NPV_1 + NPV_2 + NPV_3 = 6842 + 29635/L_s$

ü TOTAL COST

| L_s (m) | Running costs (\$) | Capital Costs (\$) | Total Costs (\$) |
|-----------|--------------------|--------------------|------------------|
| ü 10 | 9806 | 4537 | 14343 |
| ü 20 | 8324 | 5596 | 13920 |
| ü 30 | 7830 | 6849 | 14679 |
| ü 40 | 7583 | 8150 | 15733 |
| ü 50 | 7435 | 9472 | 16907 |

So, Design $L_s = 20$ m , with total cost = US \$ 13920

Example 5.7: Economic Design of Well

The following information relates to a well in an extensive alluvial aquifer:

AQUIFER: Unconfined

| | |
|-------------------------------|----------|
| Maximum depth to static water | 5 m |
| Hydraulic conductivity | 50 m/day |

PUMP:

| | |
|---|-------|
| Recommended submergence (from operating water level in well to clearance below lowest part of pump) | 2.5 m |
| Discharge delivery head (above ground level) | 1.0 m |

WELL DRAWDOWN:

| | |
|---|-----------------------|
| Drawdown given by | $S = \frac{1.3Q}{KL}$ |
| Factor of safety against deterioration in specific capacity | 25% |

COSTS:

| | |
|---|-----------------|
| Drilling and other related length costs | \$ 300/m |
| Upper well casing | \$ 120/m |
| Screen | \$ 200/m |
| Fixed costs | \$ 15,000 |
| Pumping costs | \$ 0.14QH/ year |

Where, Q: the pump discharged (m³/day).

H: the total pumping head (m).

| | |
|-----------------|-----|
| Discount factor | 8.0 |
|-----------------|-----|

- I. Obtain an expression for the total cost of the well in terms of Q and L
- II. Determine the optimum screen length for a discharge of 2000 m³/day
- III. Calculate the discharge that will provide the cheapest water for a screen length of 15 m

Answer for Example 5.7

(i)

$$s_w = 1.25x \frac{1.3Q}{50L} = 0.0325 \frac{Q}{L}$$

$$\begin{aligned} \text{Capital costs} &= \left(5 + 2.5 + 0.0325 \frac{Q}{L} \right) (300 + 120) + L(300 + 200) \\ &= 3150 + 13.65 \frac{Q}{L} + 500L \end{aligned}$$

$$\begin{aligned} \text{Operating costs} &= 0.14x Qx \left(1 + 5 + 0.0325 \frac{Q}{L} \right) x 8 \\ &= 6.72Q + 0.0364 \frac{Q^2}{L} \end{aligned}$$

$$\text{Total Cost} = 3150 + 13.65 \frac{Q}{L} + 500L + 6.72Q + 0.0364 \frac{Q^2}{L}$$

(ii)

$$\frac{\partial C}{\partial L} = -\frac{13.65Q}{L^2} + 500 - \frac{0.0364Q^2}{L^2}$$

For minimum C

$$\frac{13.65Q + 0.0364Q^2}{500} = L^2$$

For a discharge of $2000 \text{ m}^3 / \text{day}$

$$L = 18.6 \text{ m}$$

(iii)

$$\frac{C}{Q} = \frac{3150}{Q} + \frac{13.65}{L} + 500 \frac{L}{Q} + 6.72 + 0.0364 \frac{Q}{L}$$

For cheapest water

$$\frac{\partial(C/Q)}{\partial Q} = -\frac{3150}{Q^2} - \frac{500L}{Q^2} + \frac{0.0364}{L} = 0$$

So,

$$Q^2 = \frac{(500L + 3150)L}{0.0364}$$

when $L = 15 \text{ m}$

$$Q = 2095 \text{ m}^3 / \text{day}$$

Example 5.8: Economic Design of Well

Determine the optimum screen length for a well to pump 2000 m³/day to be constructed in an extensive alluvial aquifer using the following information:

AQUIFER PARAMETERS AND DRAWDOWN CONSIDERATIONS

| | |
|----------------------------------|--------------------------|
| Hydraulic conductivity | 45 m/day |
| Drawdown in the well is given by | $S_w = \frac{1.25Q}{KL}$ |
| Drawdown safety factor | 25% |

UNIT CONSTRUCTION COSTS

| | |
|---|----------|
| Drilling and other related length costs | \$ 200/m |
| Upper well casing | \$ 40/m |
| Well Screen (0.15 m diameter) | \$ 100/m |

OPERATING COSTS

| | |
|----------------------|----------------|
| Annual Pumping Costs | \$ 0.1QH/ year |
|----------------------|----------------|

Where, Q: the pump discharged (m³/day).

H: the total pumping head (m).

| | |
|-----------------|-----|
| Discount factor | 7.0 |
|-----------------|-----|

You may assume that

- (i) Well and friction losses are small.
- (ii) There are effectively no geological constraints on screen length or position.

If a 0.1 m diameter well screen (costing \$ 70/m) of the same length were to be used, what would be the extra overall cost or saving?

Assume in this case that upscreen losses are given by

$$2.0 \times 10^{-15} Q^2 L r_w^{-16/3} m$$

Answer for 5.8

1. Optimum screen length

- Capital cost (C).

$$\text{Well screen cost} = 100 L$$

$$\begin{aligned}\text{Upper well casing cost} &= 40 \times 1.25 s_w \\ &= 50 s_w\end{aligned}$$

$$\begin{aligned}\text{Drilling cost} &= 200 \times \text{drilling depth (considering the darwdown safety factor)} \\ &= 200 \times [1.25 s_w + L] \\ &= 250 s_w + 200 L\end{aligned}$$

$$\text{So, } C = 100 L + 50 s_w + 250 s_w + 200 L$$

$$C = 300 s_w + 300 L$$

- Operating cost (c).

$$\begin{aligned}c &= 0.1 Q H \\ &= 0.1 \times 200 \times 1.25 s_w\end{aligned}$$

$$c = 250 s_w$$

$$\text{But } f = 7. \text{ So, } c f = 250 s_w \times 7 = 1750 s_w$$

- Total cost (PV)

$$\begin{aligned}\text{Total cost (PV)} &= C + c f \\ &= 300 s_w + 300 L + 1750 s_w \\ &= 2050 s_w + 300 L\end{aligned}$$

$$\text{But, } s_w = \frac{1.25 Q}{KL} = \frac{1.25 \times 2000}{45L} = \frac{2000}{36L}$$

$$\begin{aligned}\text{Total cost} &= 2050 \times \frac{2000}{36L} + 300 L \\ \text{PV} &= 113888.9/L + 300 L\end{aligned}$$

$$\begin{aligned}\text{Now, } dPV/dL &= 0 \\ -113888.9 /L^2 + 300 &= 0\end{aligned}$$

Solving the equation,

$$L = 19.5 \text{ m}$$

2. The overall cost or saving

Because there are losses in the upper screen, extra drawdown occurs.

$$\begin{aligned}\text{Extra drawdown due to the upper screen losses} &= 2 * 10^{-15} Q^2 L r_w^{-\frac{16}{3}} \\ &= 2 * 10^{-15} * (2000)^2 * 19.5 * (0.05)^{-16/3} \\ &= 1.335 \text{ m}\end{aligned}$$

This should go into the drawdown term:

$$\text{Total cost (PV)} = 2050 s_w + 300 L$$

$$\text{New drawdown cost} = 2050 (s_w + 1.335)$$

$$\text{Thus the increase in cost} = 2050 * 1.335 = \text{US } \$ 2777.75$$

$$\text{Saving from the screen cost} = (100 - 70) * 19.5 = \text{US } \$ 585$$

$$\text{Hence, overall extra cost} = \text{US\$ } 2192.75$$