SESSION 13

WELL DESIGN I

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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 intednded 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.

Objectives

- **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;

Objectives

✓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.

Objectives

Water quality considerations in designing a well are:

✓General indicators of corrosive waters include:

pH< 7 , DO > 2 mg/l, Cl > 500 mg/l,

H_2S < 1 mg/l, TDS > 1000 mg/l, CO_2 > 50 mg/l

✓General indictors of encrusting water include:

pH > 7.5, Carbonate hardness > 300 mg/l, dissolved iron concentration > 2 mg/l dissolved manganese > 1 mg/l

1. 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.

2. 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 > yield, then reduce diameter of the well.
   - ✓If Q < 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

3. Information Required for Well Design

3.1 Geology

- ✓Nature and location of aquifer boundaries;
- ✓Aquifer thickness;
- ✓Depth to water;
- ✓Consolidated or unconsolidated strata;
- ✓Grain size.

3.2 Aquifer Characteristics

- ✓Confined, unconfined, leaky;
- ✓Storativity;
- ✓Hydraulic conductivity;
- ✓Recharge sources;
- ✓Water quality.

3. Information Required for Well Design

3.3 More information

Knowing geology and aquifer characteristics enables:

- ✓The intake parts of the well to be established;
- ✓Selection of the well casing to ensure the borehole is stable;
- ✓Allows computation of the likely drawdown and therefore;
- ✓Allows the pump intake point to be calculated; this in turn controls;
- ✓The diameters and length of the upper well casing required.

3. Information Required for Well Design

- The structure is permanent and in general the design cannot be easily modified after installation. The estimation of parameters used in calculations therefore needs to be conservatives.

- In many instances, it is not possible to complete the well design until the well itself is drilled. This is especially true in fissured, consolidated strata or in unconsolidated granular materials which are often heterogeneous. Consolidated, granular aquifers tend to be more uniform and are therefore easier to predict. This means that less judgment is required during drilling.

3. Information Required for Well Design

3.3.1 Fissured strata

The aim is to tap a zone of high permeability, which means that site location is crucial.

Site location: Use geological maps, satellite imagery, aerial photographs etc. to identify lineaments, faults or fracture systems where the fracture density is likely to be high. Survey the site using geophysics (electrical resistivity, electromagnetic) to provide additional information.

During drilling: Use lithological samples, driller logs and penetration rates to locate productive sections. Decide when to stop drilling.

After drilling: It may be better to abandon poor hole at this stage and try again in another location. Otherwise, screen the well, test-pump and measure yield. Decide whether to complete or abandon.

3. Information Required for Well Design

3.3.2 Granular Unconsolidated Strata

Use initial investigation and/or exploratory drilling to give:

✓Indications of likely lithologies (eg. Percentage of screenable lithologies in depth range 20-100m; range of grain size to indication of screen requirements);

✓Estimates of hydraulic conductivity, aquifer thickness and ranges of variations;

Well design, including depth of well may have to be made on site, depending on:

✓Lithological samples and description;

✓Estimates of likely hydraulic conductivity (and therefore specific capacity) from lithologies encountered and background information.

✓Casing and screen materials available on site.

4. 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 4.1) 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.

4. Well Structure

2. Well Screen (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;

4. Well Structure

3. Filter or Gravel Pack (enables good flow to the well, without pumping fine-grained materials)

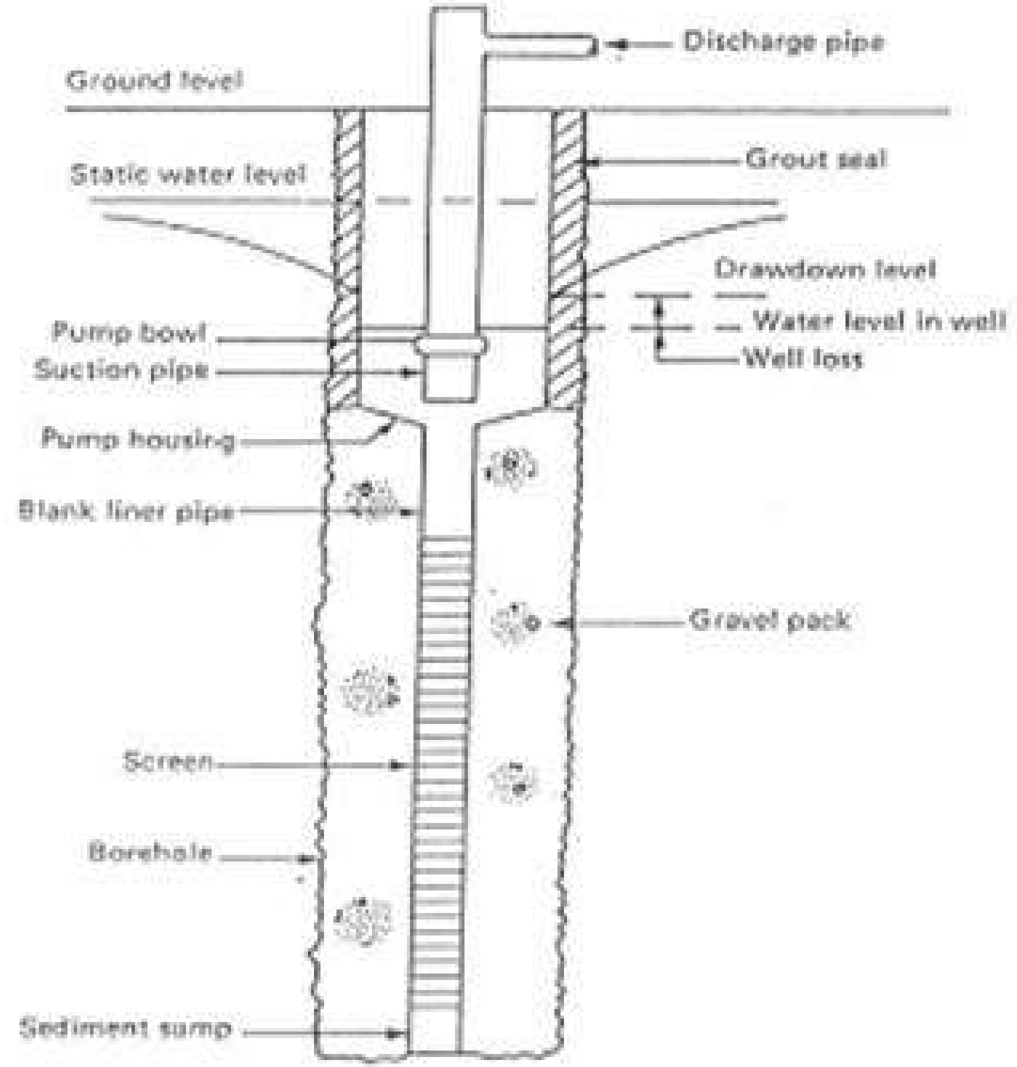
✓Material;
✓Grading;

4. Pump
✓Type;
✓Location;

5. Drilled hole
✓Dimensions (depth, diameter);
✓Drilling method

4. Well Structure

Figure 4.1: components of a typical well



4. Well Structure

4.1 Upper Well Casing and Pump Housing

4.1.1 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 pump operating level is determined from the minimum anticipated pumping water level which can be calculated from the lowest anticipated static water level (H) and the anticipated drawdown at the well (sw). A safety margin (SF) should be added to make allowance for:

✓ The variation in aquifer transmissivity due to aquifer heterogeneity;
✓ Well deterioration;
✓ Well energy losses;
✓ Future contingencies for well interference or variations in static water level;

4. Well Structure

So, the length of the upper casing becomes;

$$L = H + S_w + SF + PR$$

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;

4. Well Structure

- 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.

4. Well Structure

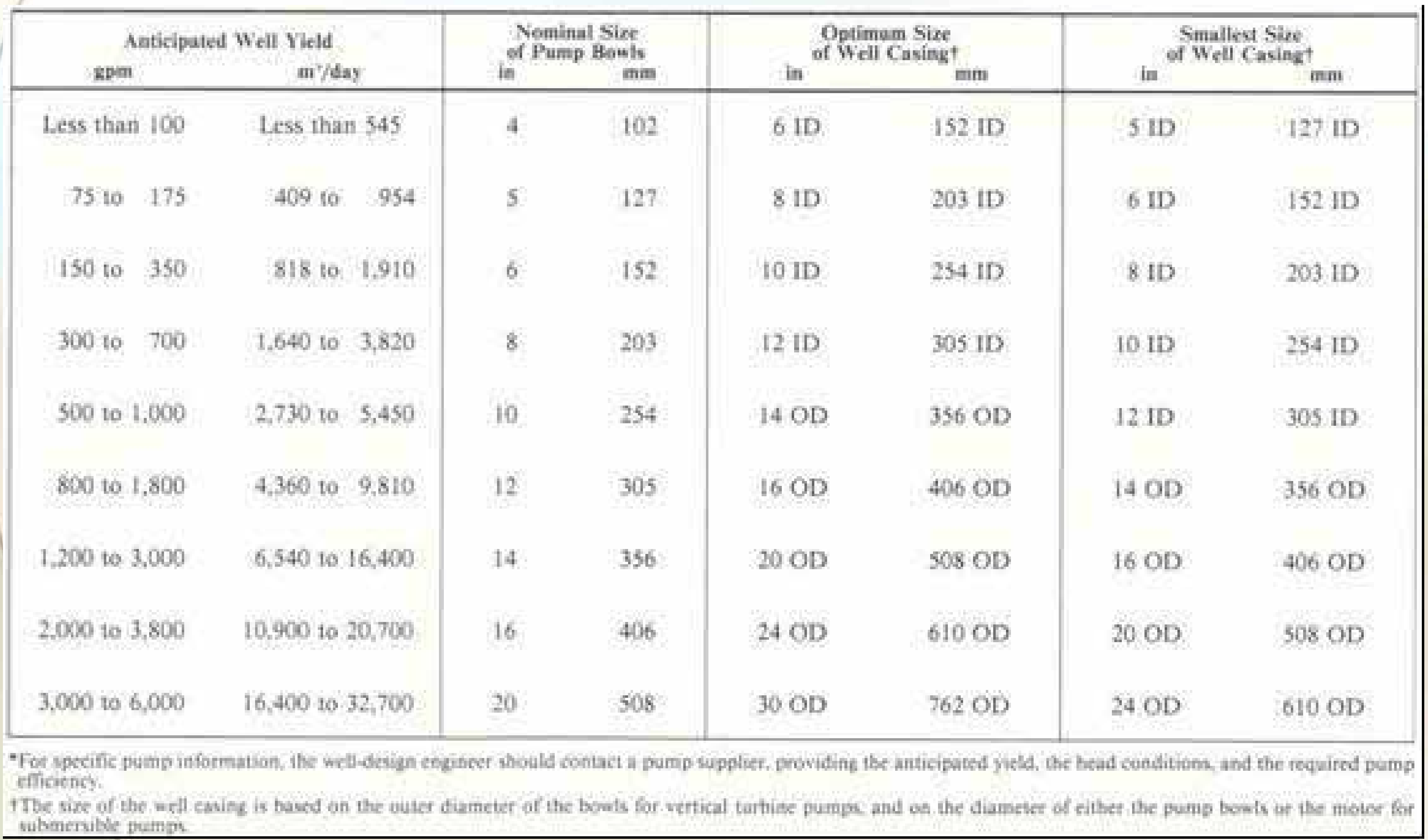
4.1.2 Diameter

- The upper well casing is sized to accommodate the pump. 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 4.1 shows the recommended well diameters for various pumping rates

4. Well Structure

Table 4.1: Recommended well Diameters for various pumping rate* (after Driscoll,1989)



Anticipated Well Yield gpm	Anticipated Well Yield m³/day	Nominal Size of Pump Bowls in	Nominal Size of Pump Bowls mm	Optimum Size of Well Casing† in	Optimum Size of Well Casing† mm	Smallest Size of Well Casing† in	Smallest Size of Well Casing† mm
Less than 100	Less than 545	4	102	6 ID	152 ID	5 ID	127 ID
75 to 175	409 to 954	5	127	8 ID	203 ID	6 ID	152 ID
150 to 350	818 to 1,910	6	152	10 ID	254 ID	8 ID	203 ID
300 to 700	1,640 to 3,820	8	203	12 ID	305 ID	10 ID	254 ID
500 to 1,000	2,730 to 5,450	10	254	14 OD	356 OD	12 ID	305 ID
800 to 1,800	4,360 to 9,810	12	305	16 OD	406 OD	14 OD	356 OD
1,200 to 3,000	6,540 to 16,400	14	356	20 OD	508 OD	16 OD	406 OD
2,000 to 3,800	10,900 to 20,700	16	406	24 OD	610 OD	20 OD	508 OD
3,000 to 6,000	16,400 to 32,700	20	508	30 OD	762 OD	24 OD	610 OD

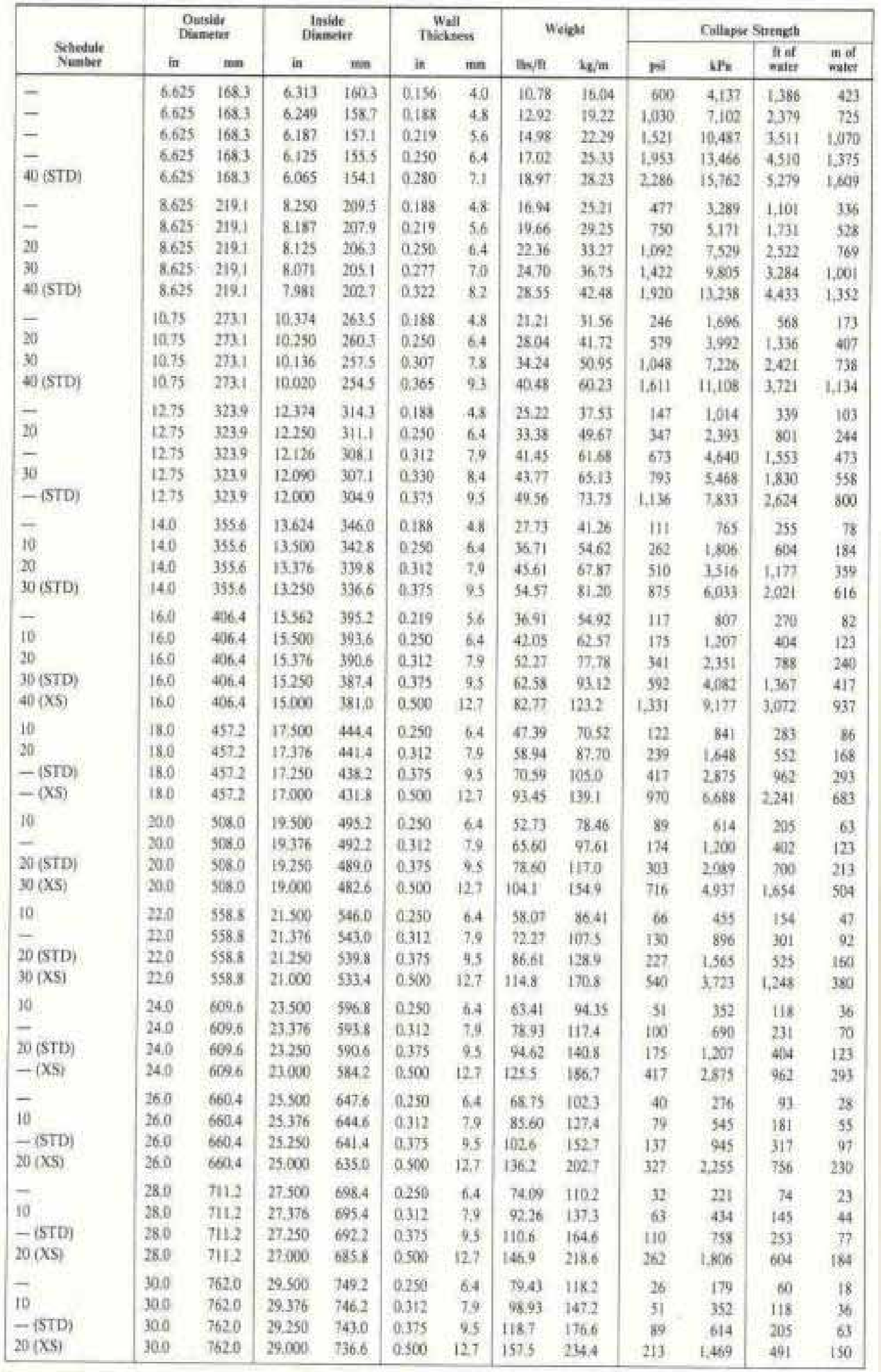
*For specific pump information, the well-design engineer should contact a pump supplier, providing the anticipated yield, the head conditions, and the required pump efficiency.

†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.

4. Well Structure

4.1.3 Thickness

Table 4.2: Physical dimensions of common pipe sizes. (after Driscoll, 1989)



Schedule Number	Outside Diameter		Inside Diameter		Wall Thickness		Weight		Collapse Strength			
	in	mm	in	mm	in	mm	lbs/ft	kg/m	psi	kPa	ft of water	m of water
—	6.625	168.3	6.313	160.3	0.156	4.0	10.78	16.04	600	4,137	1,386	423
—	6.625	168.3	6.249	158.7	0.188	4.8	12.92	19.22	1,030	7,102	2,379	725
—	6.625	168.3	6.187	157.1	0.219	5.6	14.98	22.29	1,521	10,487	3,511	1,070
—	6.625	168.3	6.125	155.5	0.250	6.4	17.02	25.33	1,953	13,466	4,510	1,375
40 (STD)	6.625	168.3	6.065	154.1	0.280	7.1	18.97	28.23	2,286	15,762	5,279	1,609
—	8.625	219.1	8.250	209.5	0.188	4.8	16.94	25.21	477	3,289	1,101	336
—	8.625	219.1	8.187	207.9	0.219	5.6	19.66	29.25	750	5,171	1,731	528
20	8.625	219.1	8.125	206.3	0.250	6.4	22.36	33.27	1,092	7,529	2,522	769
30	8.625	219.1	8.071	205.1	0.277	7.0	24.70	36.75	1,422	9,805	3,284	1,001
40 (STD)	8.625	219.1	7.981	202.7	0.322	8.2	28.55	42.48	1,920	13,238	4,433	1,352
—	10.75	273.1	10.374	263.5	0.188	4.8	21.21	31.56	246	1,696	568	173
20	10.75	273.1	10.250	260.3	0.250	6.4	28.04	41.72	579	3,992	1,336	407
30	10.75	273.1	10.136	257.5	0.307	7.8	34.24	50.95	1,048	7,226	2,421	738
40 (STD)	10.75	273.1	10.020	254.5	0.365	9.3	40.48	60.23	1,611	11,108	3,721	1,134
—	12.75	323.9	12.374	314.3	0.188	4.8	25.22	37.53	147	1,014	339	103
20	12.75	323.9	12.250	311.1	0.250	6.4	33.38	49.67	347	2,393	801	244
—	12.75	323.9	12.126	308.1	0.312	7.9	41.45	61.68	673	4,640	1,553	473
30	12.75	323.9	12.090	307.1	0.330	8.4	43.77	65.13	793	5,468	1,830	558
— (STD)	12.75	323.9	12.000	304.9	0.375	9.5	49.56	73.75	1,136	7,833	2,624	800
—	14.0	355.6	13.624	346.0	0.188	4.8	27.73	41.26	111	765	255	78
10	14.0	355.6	13.500	342.8	0.250	6.4	36.71	54.62	262	1,806	604	184
20	14.0	355.6	13.376	339.8	0.312	7.9	45.61	67.87	510	3,516	1,177	359
30 (STD)	14.0	355.6	13.250	336.6	0.375	9.5	54.57	81.20	875	6,033	2,021	616
—	16.0	406.4	15.562	395.2	0.219	5.6	36.91	54.92	117	807	270	82
10	16.0	406.4	15.500	393.6	0.250	6.4	42.05	62.57	175	1,207	404	123
20	16.0	406.4	15.376	390.6	0.312	7.9	52.27	77.78	341	2,351	788	240
30 (STD)	16.0	406.4	15.250	387.4	0.375	9.5	62.58	93.12	592	4,082	1,367	417
40 (XS)	16.0	406.4	15.000	381.0	0.500	12.7	82.77	123.2	1,331	9,177	3,072	937
10	18.0	457.2	17.500	444.4	0.250	6.4	47.39	70.52	122	841	283	86
20	18.0	457.2	17.376	441.4	0.312	7.9	58.94	87.70	239	1,648	552	168
— (STD)	18.0	457.2	17.250	438.2	0.375	9.5	70.59	105.0	417	2,875	962	293
— (XS)	18.0	457.2	17.000	431.8	0.500	12.7	93.45	139.1	970	6,688	2,241	683
10	20.0	508.0	19.500	495.2	0.250	6.4	52.73	78.46	89	614	205	63
—	20.0	508.0	19.376	492.2	0.312	7.9	65.60	97.61	174	1,200	402	123
20 (STD)	20.0	508.0	19.250	489.0	0.375	9.5	78.60	117.0	303	2,089	700	213
30 (XS)	20.0	508.0	19.000	482.6	0.500	12.7	104.1	154.9	716	4,937	1,654	504
10	22.0	558.8	21.500	546.0	0.250	6.4	58.07	86.41	66	455	154	47
—	22.0	558.8	21.376	543.0	0.312	7.9	72.27	107.5	130	896	301	92
20 (STD)	22.0	558.8	21.250	539.8	0.375	9.5	86.61	128.9	227	1,565	525	160
30 (XS)	22.0	558.8	21.000	533.4	0.500	12.7	114.8	170.8	540	3,723	1,248	380
10	24.0	609.6	23.500	596.8	0.250	6.4	63.41	94.35	51	352	118	36
—	24.0	609.6	23.376	593.8	0.312	7.9	78.93	117.4	100	690	231	70
20 (STD)	24.0	609.6	23.250	590.6	0.375	9.5	94.62	140.8	175	1,207	404	123
— (XS)	24.0	609.6	23.000	584.2	0.500	12.7	125.5	186.7	417	2,875	962	293
—	26.0	660.4	25.500	647.6	0.250	6.4	68.75	102.3	40	276	93	28
10	26.0	660.4	25.376	644.6	0.312	7.9	85.60	127.4	79	545	181	55
— (STD)	26.0	660.4	25.250	641.4	0.375	9.5	102.6	152.7	137	945	317	97
20 (XS)	26.0	660.4	25.000	635.0	0.500	12.7	136.2	202.7	327	2,255	756	230
—	28.0	711.2	27.500	698.4	0.250	6.4	74.09	110.2	32	221	74	23
10	28.0	711.2	27.376	695.4	0.312	7.9	92.26	137.3	63	434	145	44
— (STD)	28.0	711.2	27.250	692.2	0.375	9.5	110.6	164.6	110	758	253	77
20 (XS)	28.0	711.2	27.000	685.8	0.500	12.7	146.9	218.6	262	1,806	604	184
—	30.0	762.0	29.500	749.2	0.250	6.4	79.43	118.2	26	179	60	18
10	30.0	762.0	29.376	746.2	0.312	7.9	98.93	147.2	51	352	118	36
— (STD)	30.0	762.0	29.250	743.0	0.375	9.5	118.7	176.6	89	614	205	63
20 (XS)	30.0	762.0	29.000	736.6	0.500	12.7	157.5	234.4	213	1,469	491	150

4. Well Structure

4.2 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

4. Well Structure

4.2.1 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.

4. Well Structure

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

1. 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)
2. 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 4.2). Costs of additional screen must be balanced against the benefits of reduced drawdown.

4. Well Structure

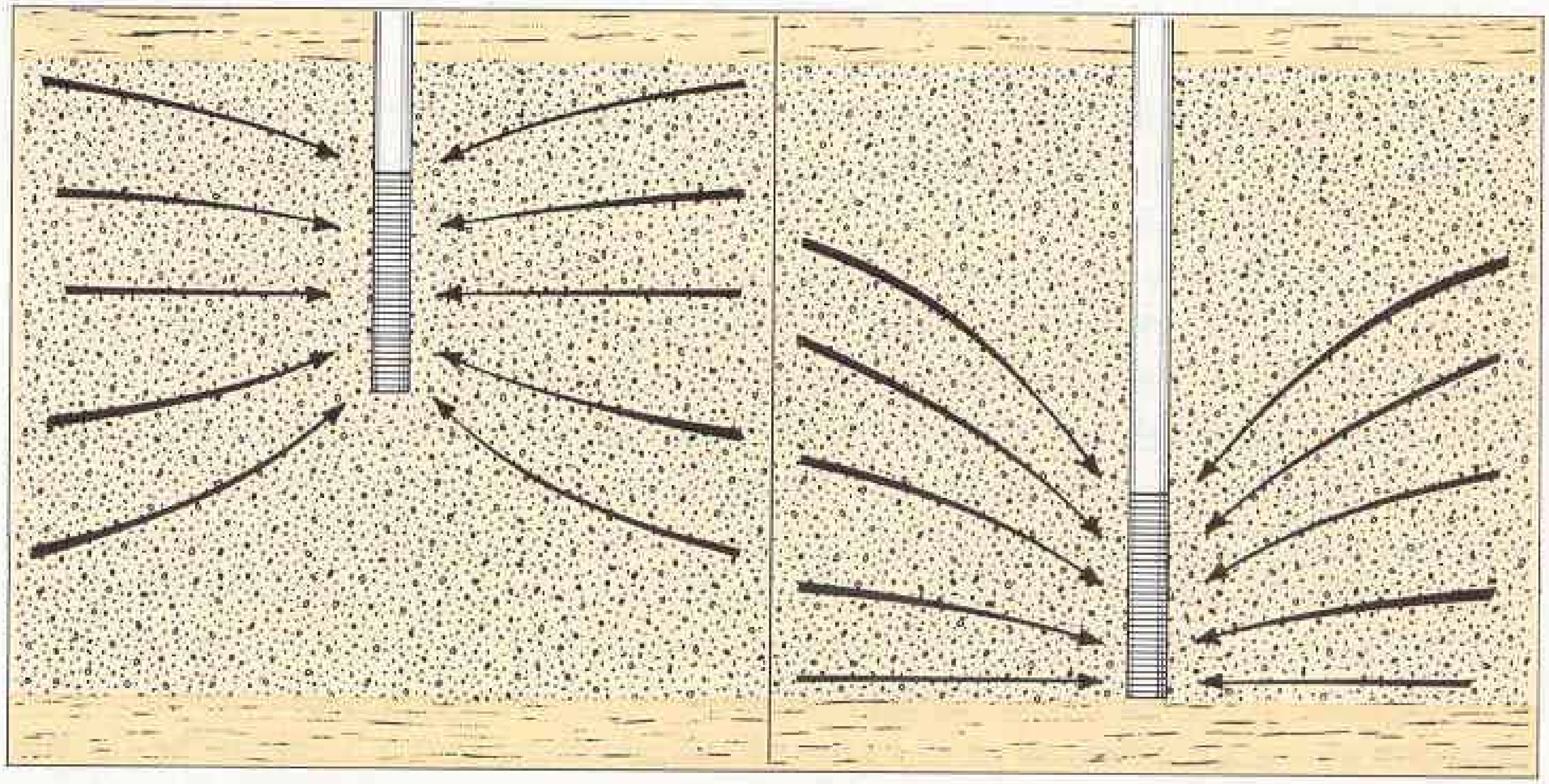


Figure 4.2 partial penetrations when the intake portion of the well is less than the full thickness of the aquifer. This causes distortion of the flow lines and greater head losses.

4. Well Structure

Field identification of screenable aquifer will largely be made on the basis of the lithological log. Clays and unproductive sections are not 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 4.3). This:

✓Protects the material from being eroded thereby placing the casing under stress.

✓Protects the pump from the ill effects of pumping sand.

4. Well Structure

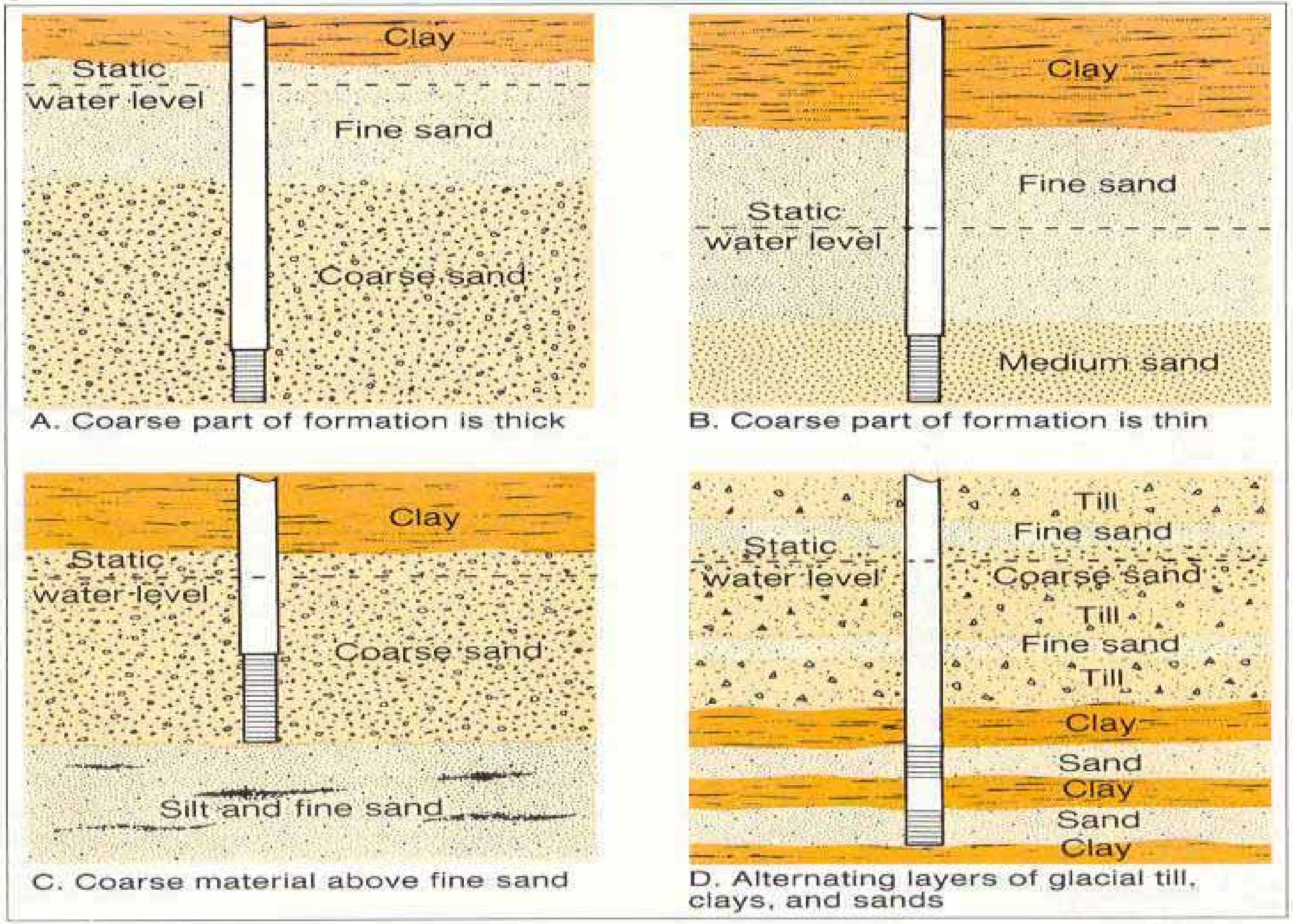


Figure 4.3 Suggested positioning of well screens in various stratified water-bearing formations

4. Well Structure

4.2.1.1 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.

4. Well Structure

✓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 4.4**).

4. Well Structure

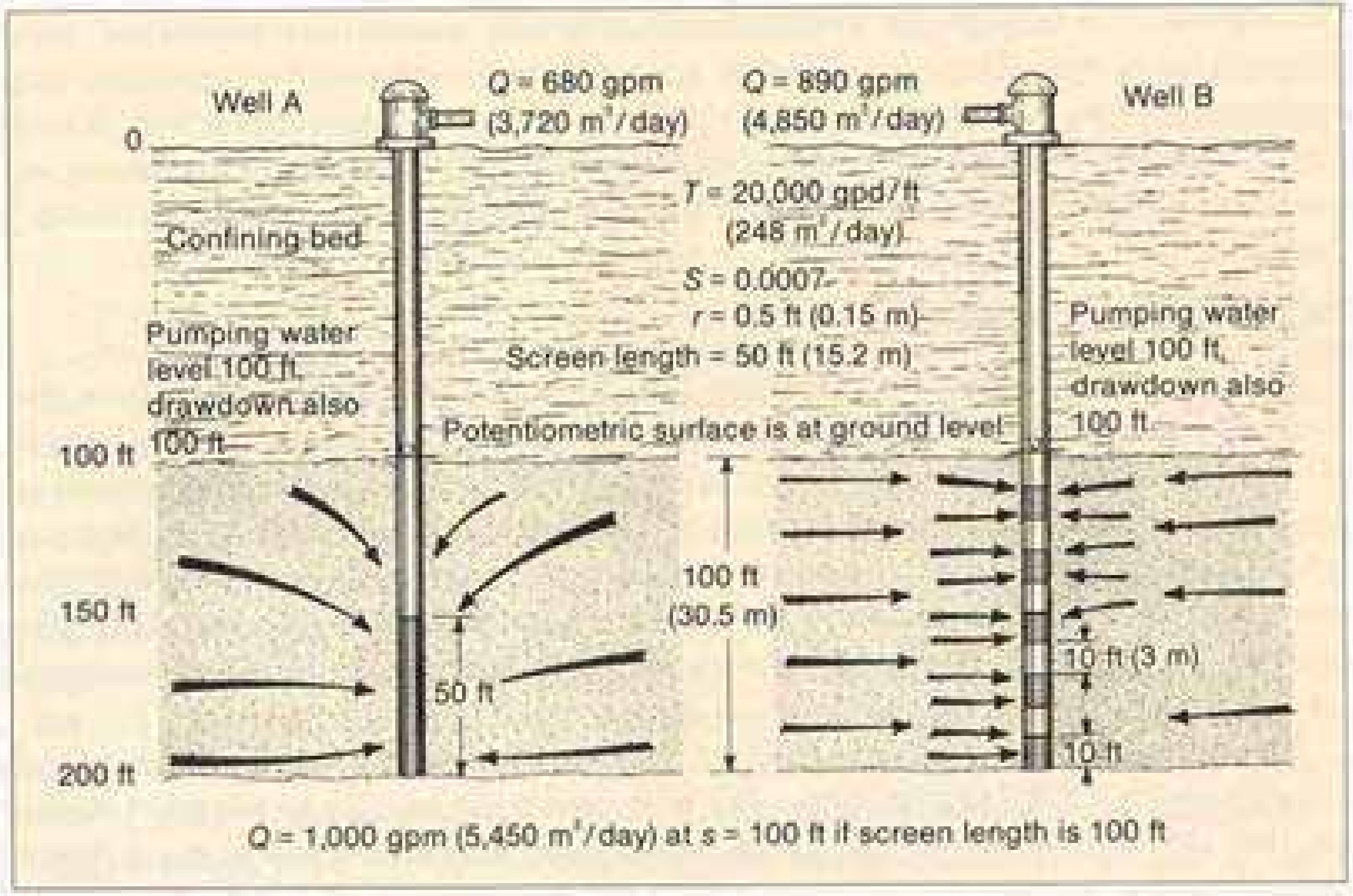


Figure 4.4: Flow line convergence to a screened interval is minimized and well performance can be improved by using sections of well screen in a thick aquifer to reduce the effect of partial penetration. Total screen length is the same in both wells.

4. Well Structure

4.2.1.2 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, a sand that has an effective grain size of 0.2 mm will have about 4 times the hydraulic conductivity of a 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.

4. Well Structure

- ✓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 need to be screened.

4. Well Structure

4.2.1.3 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,

4. Well Structure

✓Because of the convergence of flow lines and induced turbulence, pumping a water-table well at a rate at which the drawdown exceeds two-thirds of the saturated thickness is not practical. For example, pumping at 65% of available drawdown produces about 88% of the maximum yield, which is 68% of the maximum obtainable specific capacity (**Figure 4.5**); increasing the drawdown to 95% produces 99% of the maximum yield. Hence, only an 11% increase in yield is achieved by a 46% increase in drawdown.

4. Well Structure

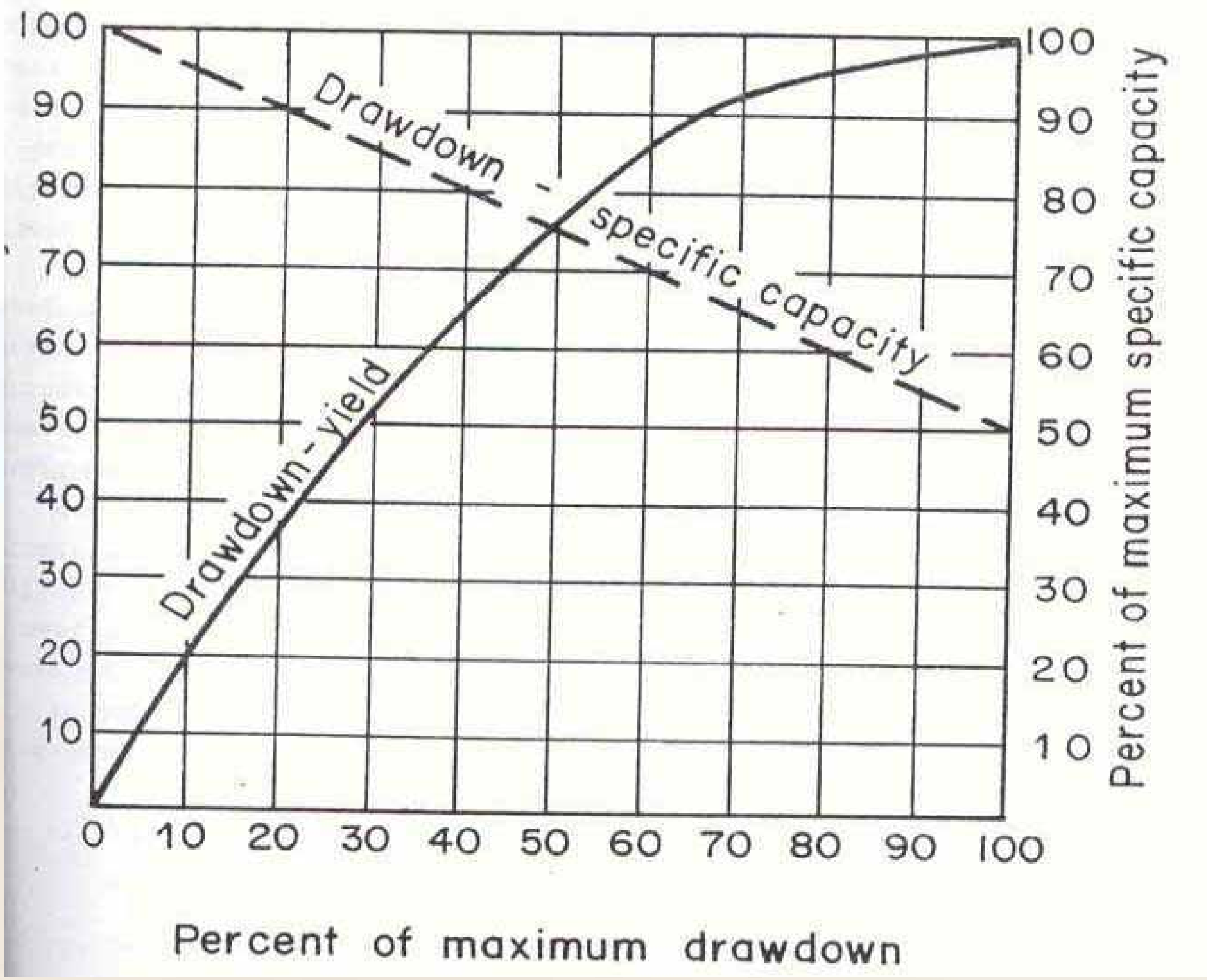


Figure 4.5: Relation of percent drawdown to yield and of percent drawdown to specific capacity for a well in a homogeneous unconfined aquifer (modified from Butler, 1957)

4. Well Structure

4.2.1.4 Heterogeneous Unconfined (Water-Table) Aquifer

✓Screen or screen sections in a heterogeneous unconfined aquifer generally are positioned in the most permeable layers in the lower part of the aquifer to maximize the available drawdown. As in a homogeneous unconfined aquifer, the total screen length needs to be about one-third of the aquifer thickness.

✓The largest permeability zones commonly occur at or close to the water table. This occurrence is a result of the winnowing action due to the normal fluctuations of the water table. In this situation, the available drawdown and production from the well may be limited in the larger permeability zone by the underlying, less permeable materials.

4. Well Structure

4.2.2 Well Screen Diameter

✓Energy losses within the well structure are largely accounted for by:

✓Screen entrance losses (energy lost as water passes from the outside to the inside of the well screen) (**Figure 4.6**).

4. Well Structure

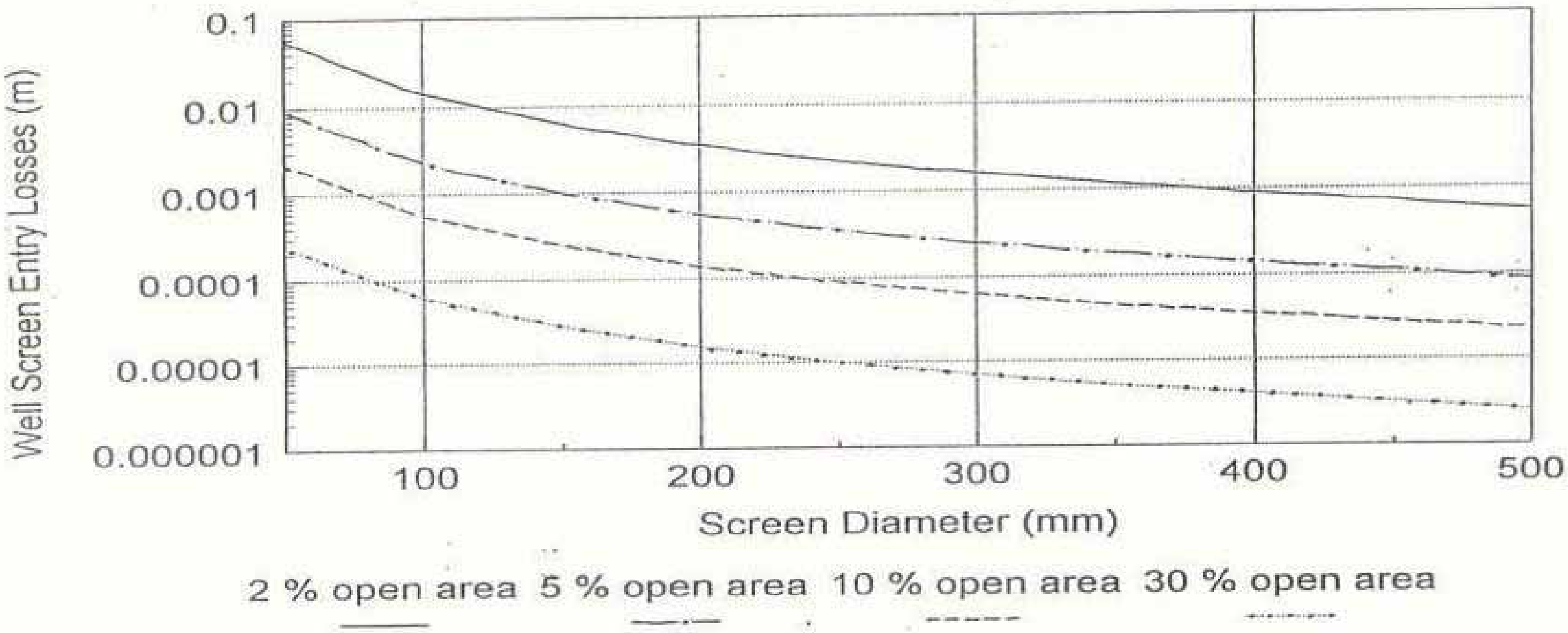


Figure 4.6: Relation of well screen entry losses to screen diameter with different open areas.

4. Well Structure

✓Screen upflow losses (energy loss due to friction as the water moves vertically within the well casing) (**Figure 4.7**).

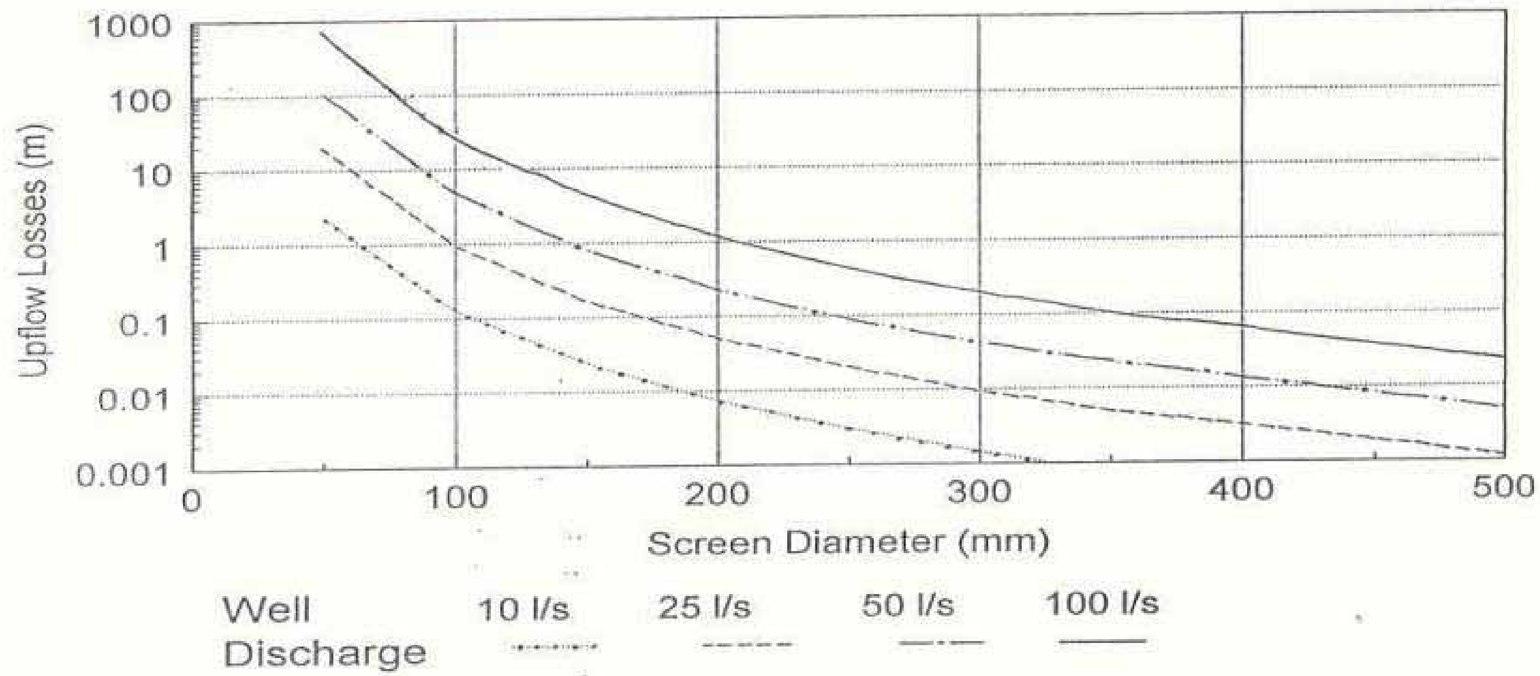


Figure 4.7: Relation of upflow losses to screen diameter with different will discharge.

4. Well Structure

Screen entrance losses are generally extremely small compared to the screen upflow losses.

Many texts recommend the use of approach velocities and screen entrance velocities. The use of these criteria in design has now largely been discredited.

4. Well Structure

Upflow losses

Method 1: Bakiewicz, Milne and Pattle 1985.

$$\Delta h = 3.428\, q^2\, n^2\, L_s\, D^{-16/3}$$

where,

Δh is the upflow head loss (in meters)

q is the flow rate into the screen (the screen flux), Which is assumed constant throughout the screen length and is therefore given by q=Q/L (in m^2/sec).

n is the Manning's roughness coefficient, established as 0.01 for plain pipe, 0.013 for slotted pipe and 0.018 for wire wound pipe screens.

D screen diameter.

4. Well Structure

Method 2: Barker and Herbert, 1992.

$$\Delta h = Q^2 \left[\frac{\alpha L_s}{4} + \frac{\beta}{3} \right]$$

where, α and β are parameters dependent upon screen type and strongly upon diameter. These are defined as:

$$\beta = \frac{32}{g \pi^2 D^4} \qquad \alpha = \frac{32 f}{4 \pi^2 g D^5}$$

where,

g	is the gravitational acceleration
D	diameter
f	is a pipe friction factor. (values of 0.015 for slotted pipe, 0.018 for perforated pipe and 0.033 for wire-wound screen have been suggested)

4. Well Structure

Rule of Thumb

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.

4. Well Structure

- ✓ If cost of increasing diameter is significant, and no significant reduction is 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 diameter of the well screen can be varied without greatly affecting the specific capacity or well yield (see Figure 4.8). For example, doubling the screen diameter increases the specific capacity of the well by 10%, if all other factors remain constant. The effective well diameter may be increased by the selection of a slot size that enables a greater area to be achieved through the use of a gravel or sand pack around the well screen.

4. Well Structure

- ✓ 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.

4. Well Structure

- ✓ 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.

4. Well Structure

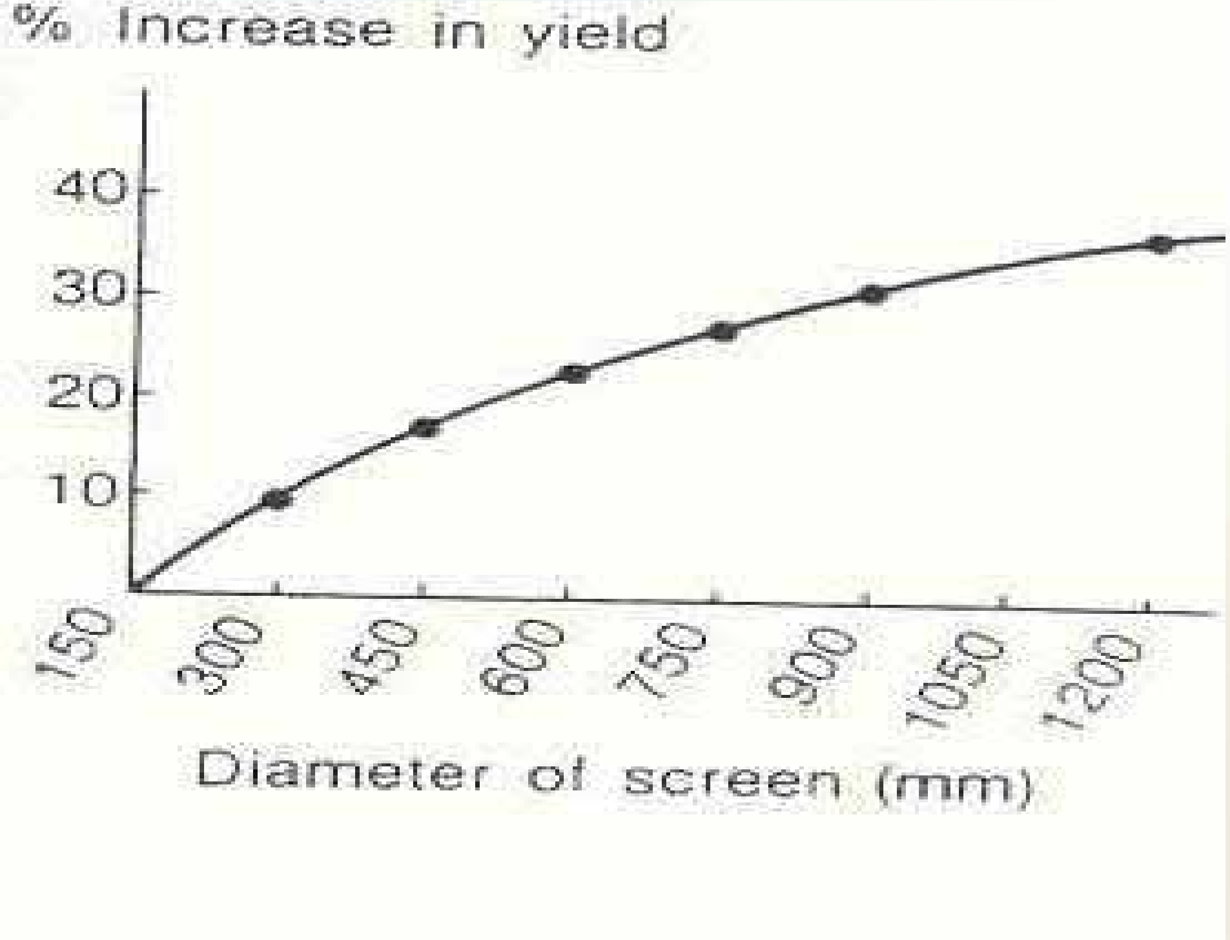


Figure 4.8: The theoretical increase in yield with increase in well diameter. Expressed as % increase over yield of a 150 mm diameter well

SESSION 14

WELL DESIGN II

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4. Well Structure

4.3 Slot Types and Open Area

Well screens are manufactured from a variety of materials and range from crude hand-made contrivance (**Figure 4.9**) to highly efficient and long life models made on machines costing hundreds of thousands of dollars (**Figure 4.10**). 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

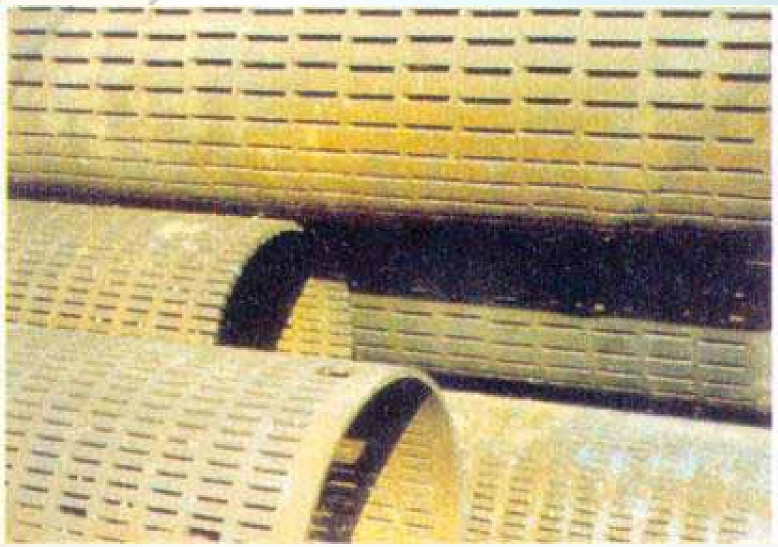
4. Well Structure

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.

4. Well Structure



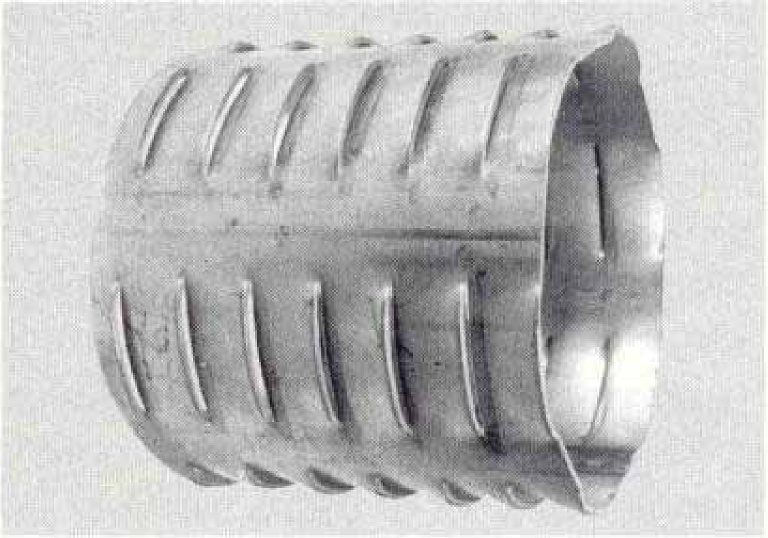
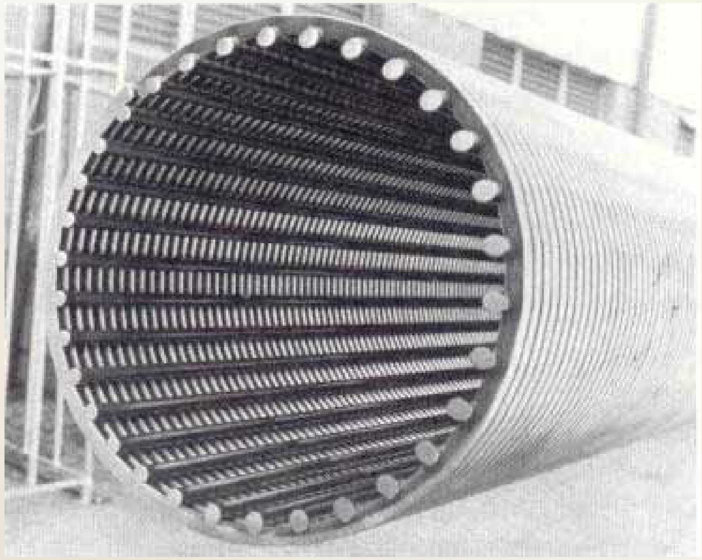


Figure: 4.10 Continuous-slot screens are widely used for water wells. They are constructed by winding cold-rolled, triangular-shaped wire around a circular array of longitudinal rods.



4. Well Structure

- ✓ Extensive experience has shown that screens with the following characteristics provide the best service in most geologic conditions and will satisfy the varying physical characteristics of the aquifers.

- ✓ 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 4.11**)

4. Well Structure

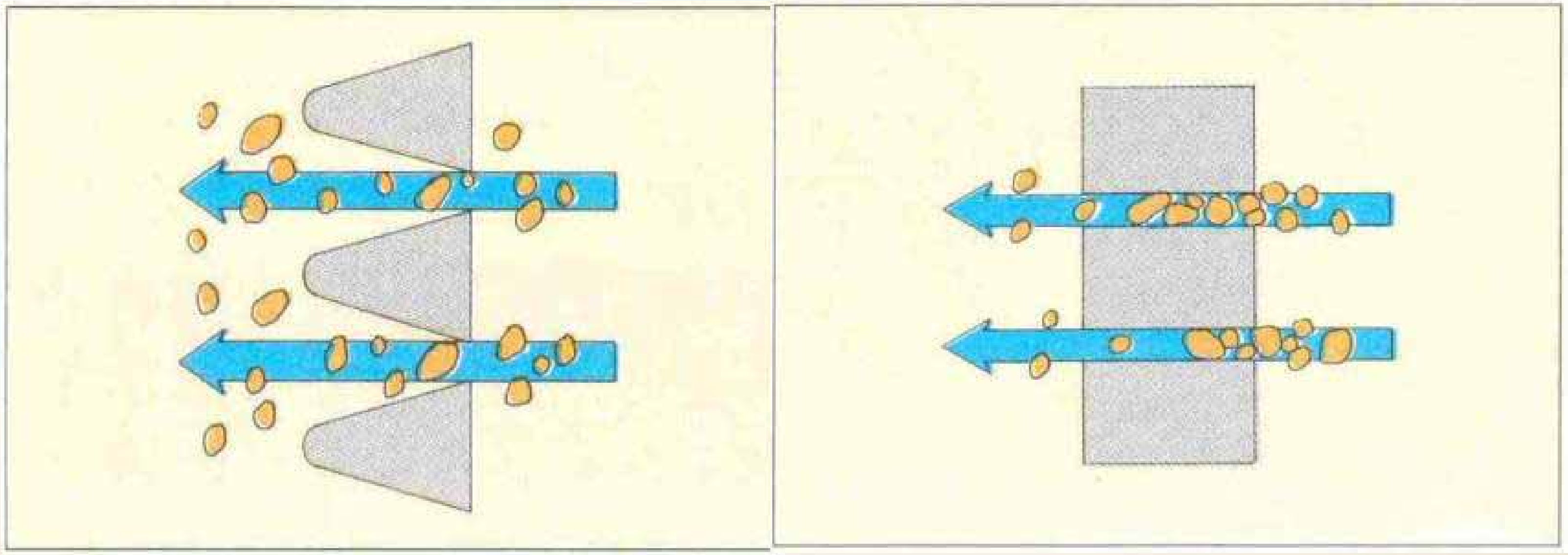


Figure 4.11: V-shaped slot openings reduce clogging where straight cut, punched or gauze-type openings can be clogged by elongate or slightly oversize particles

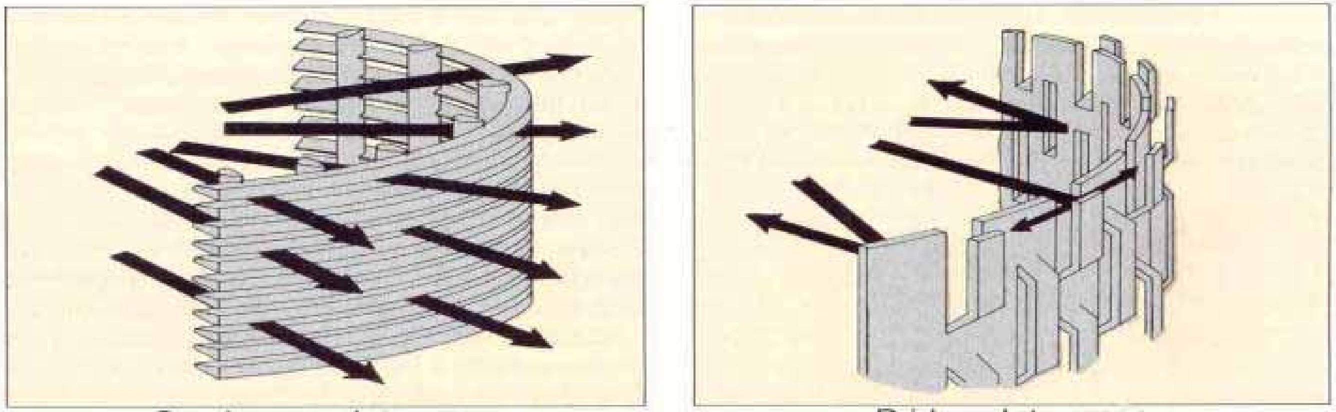
4. Well Structure

4.3.1 Screen Slot Types

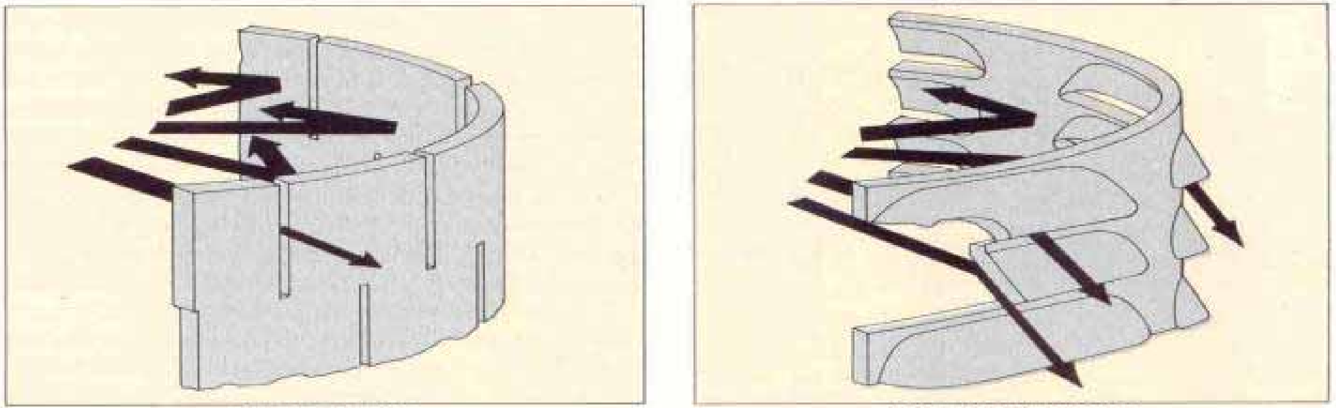
There are mainly four types of well screen (see **Figure 4.12**), they are:

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

4. Well Structure


Continuous-slot screen

Bridge-slot screen


Slotted pipe

Louvered screen

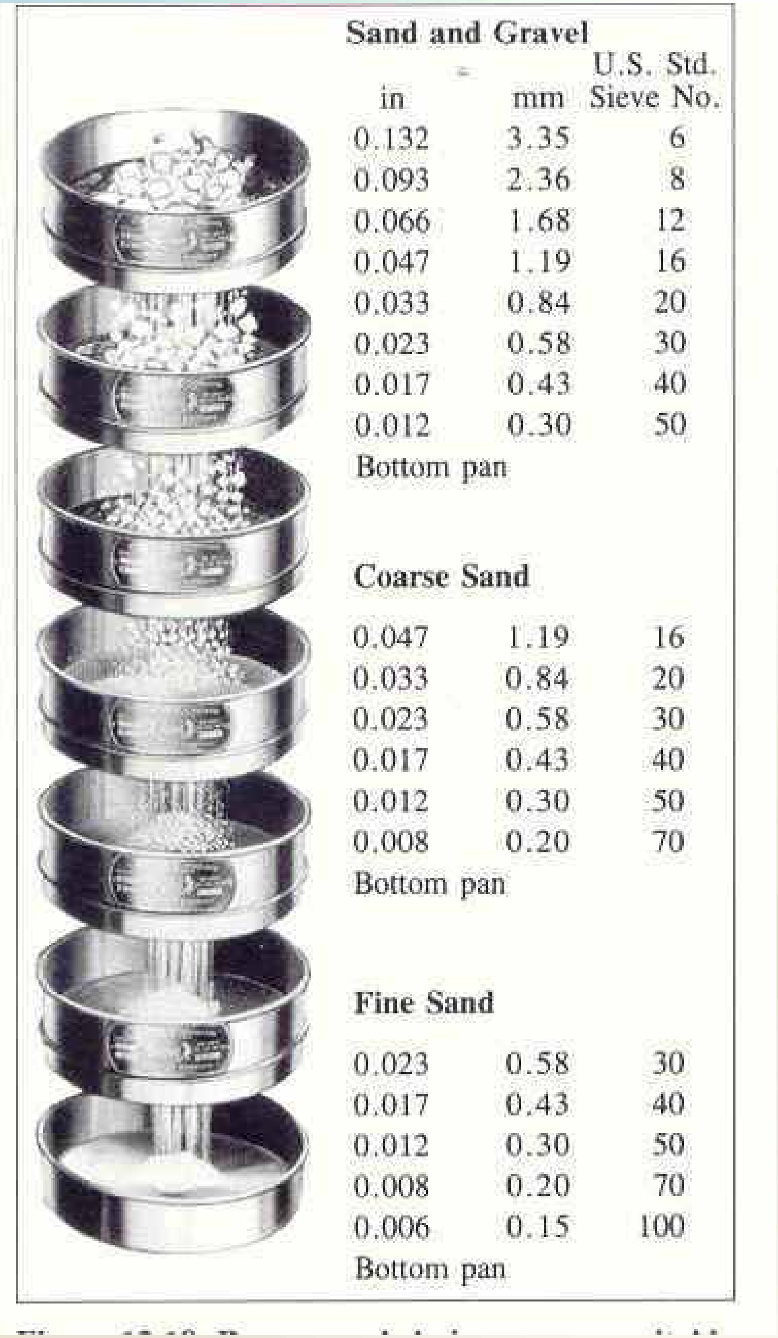
Figure 4.12: Configuration of the slot openings

4. Well Structure

4.3.2 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 (see Figure 4.13). 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 4.14**)

4. Well Structure



Sand and Gravel

in	mm	U.S. Std. Sieve No.
0.132	3.35	6
0.093	2.36	8
0.066	1.68	12
0.047	1.19	16
0.033	0.84	20
0.023	0.58	30
0.017	0.43	40
0.012	0.30	50
Bottom pan		

Coarse Sand

in	mm	U.S. Std. Sieve No.
0.047	1.19	16
0.033	0.84	20
0.023	0.58	30
0.017	0.43	40
0.012	0.30	50
0.008	0.20	70
Bottom pan		

Fine Sand

in	mm	U.S. Std. Sieve No.
0.023	0.58	30
0.017	0.43	40
0.012	0.30	50
0.008	0.20	70
0.006	0.15	100
Bottom pan		

Figure 4.13: Recommended sieve groups suitable for sieving various classes of unconsolidated sediments.

4. Well Structure

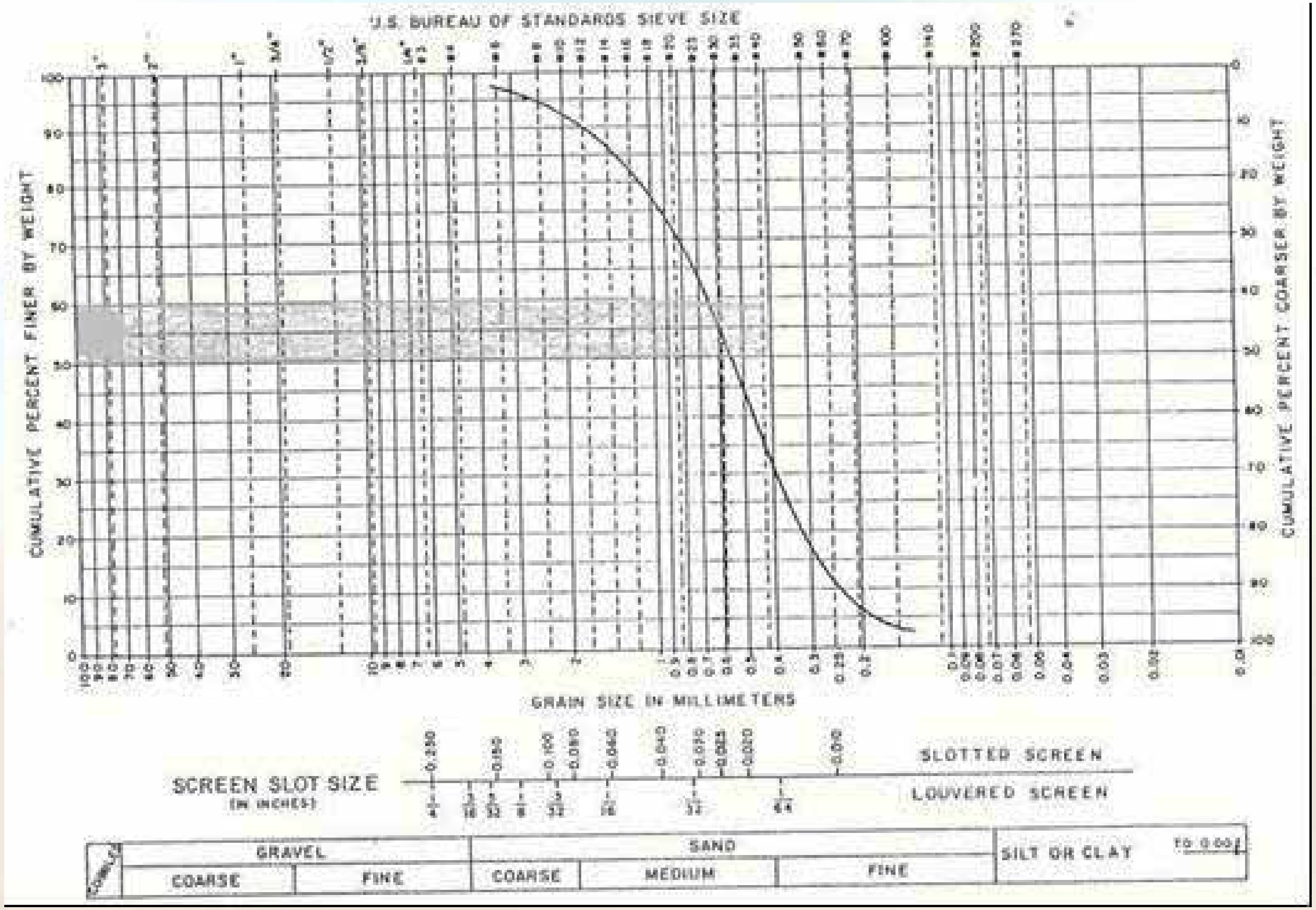


Figure 4.14: Selection of screen slot size for uniform sand

4. Well Structure

- ✓ The 60-perecnt 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-perecnt passing value is used if the water is corrosive of if there is doubt as to the reliability of the sample; the 50-percent passing value is the more conservative design.

4. Well Structure

There is greater latitude in selecting slot size for a homogeneous formation that consists of sand and gravel. The grain-size curve for sand and gravel is flatter than the curve for sand. Hence, the slot size is less critical for the passage of material than when the curve is steep. To determine the slot opening in this special case, a uniformity coefficient ,U_c ,can be calculated by:

$$U_c = \frac{D_{60}}{D_{10}}$$

Where,

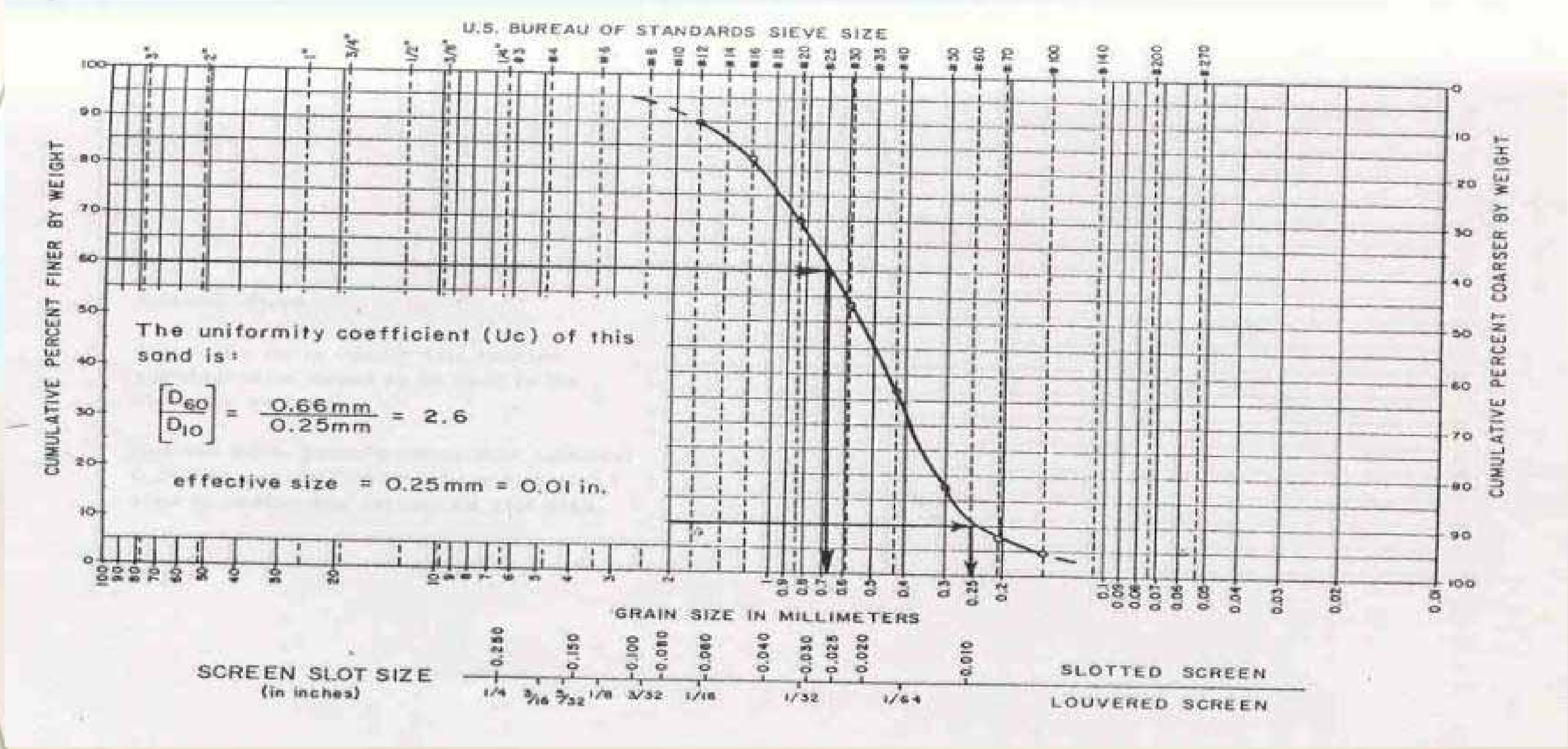
D_{60} grain size in which 60 percent of sample is passed

D_{10} grain size in which 10 percent of sample is passed (effective diameter)

4. Well Structure

- ✓ The uniformity coefficient is the average slope of the sand curve between the 60% and the 10% passed particle size. The larger the value, the more uniform is the grading of the sand between these limits; smaller values represent less uniform grading (see Figure 4.15).

4. Well Structure



The uniformity coefficient (Uc) of this sand is:

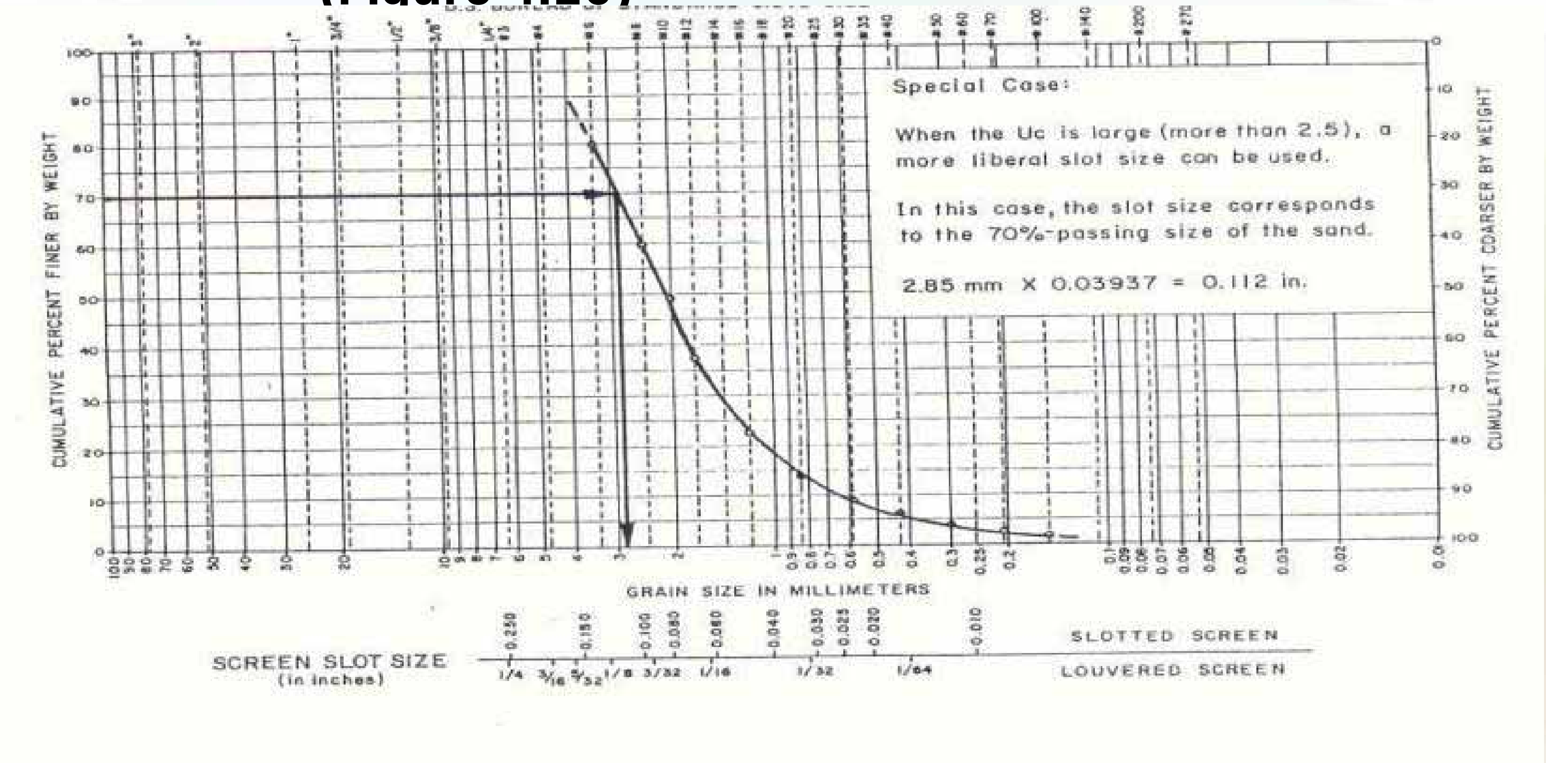
$$\left[\frac{D_{60}}{D_{10}}\right] = \frac{0.66\,\text{mm}}{0.25\,\text{mm}} = 2.6$$

effective size = 0.25mm = 0.01 in.

Figure 4.15: Grain-size curve for lithologic unit in moderate grading

4. Well Structure

- ✓ However, when the curve is flat (or **U_c** is greater than **2.5**), which indicates mostly sand and gravel, the 70% passing size of sand is used to determine the corresponding slot size **(Figure 4.16)**



Special Case:

When the Uc is large (more than 2.5), a more liberal slot size can be used.

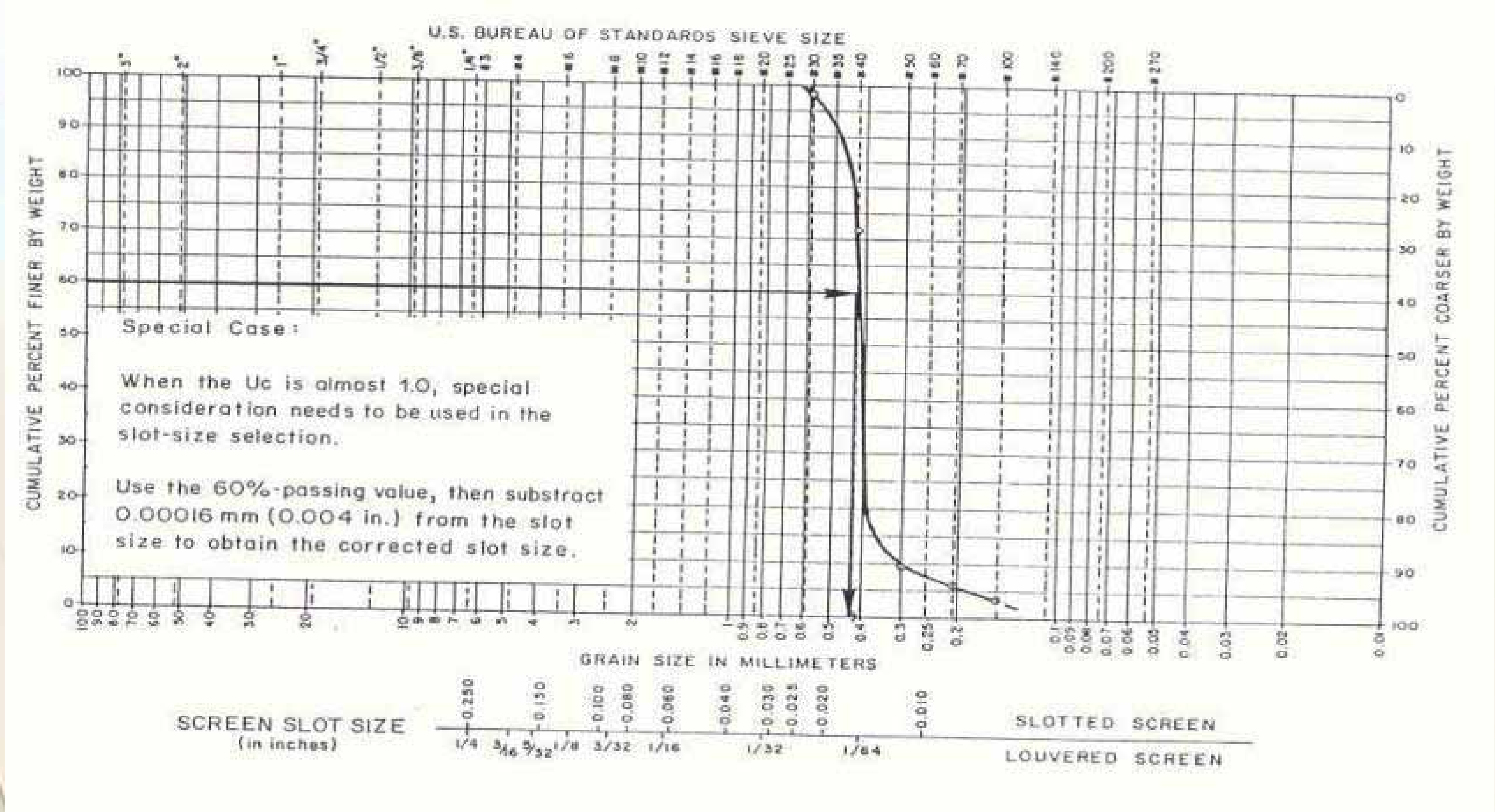
In this case, the slot size corresponds to the 70%-passing size of the sand.

2.85 mm X 0.03937 = 0.112 in.

Figure 4.16: Grain-size curve of poorly graded sand and gravel.

4. Well Structure

- ✓ Two other special cases in which the (U_c) is almost **1.0** or in which only a small percentage of the sand-size part of the sample is above the 60% passing grain-size, are shown in **Figures 4.17 and 4.18**, respectively, these cases need special considerations for slot-size selection.



coefficient of 1.

4. Well Structure

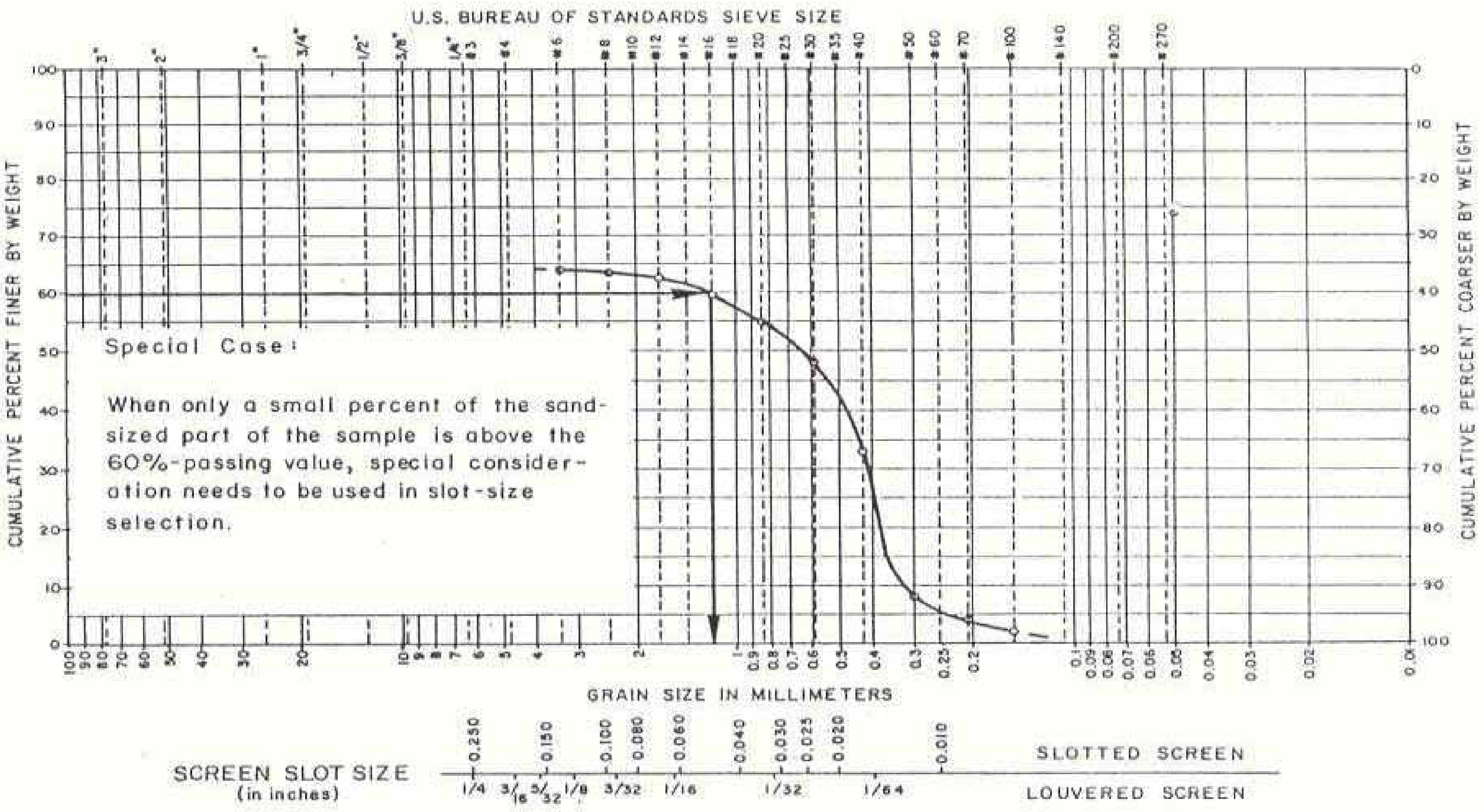


Figure 4.18: Grain-size curve for sample that has a small percentage of material above 60% passing (D_{60})

4. Well Structure

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.

4. Well Structure

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 4.19**):

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

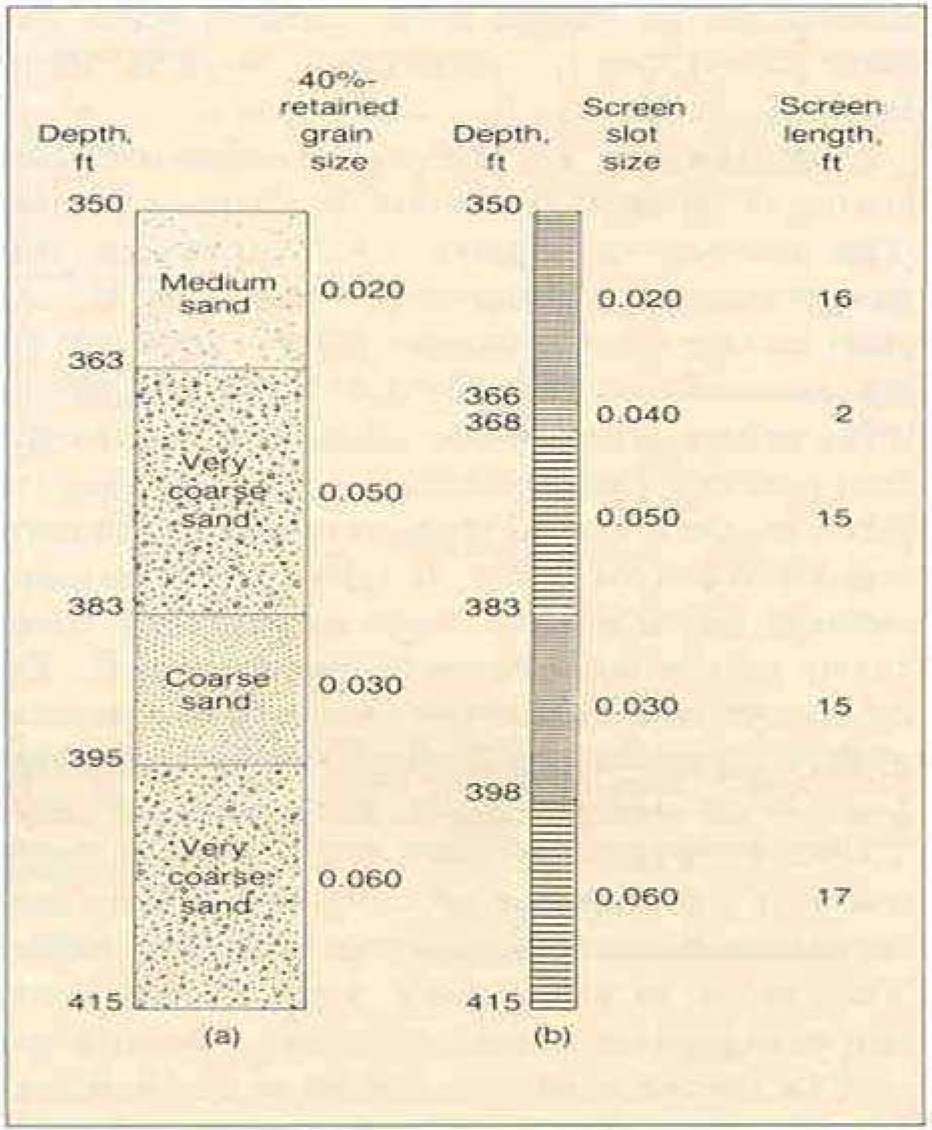
b. The slot size in the coarse material should not be more than double the slot size for the overlying finer material. Doubling of the slot size should be done over screen increments of 2 ft (0.6m) or more.

4. Well Structure

Figure 4.19

(a)Stratigraphic section that will be screened with slot sizes corresponding to various layers.

(b)(b) Sketch of screen showing the slot sizes selected on the previous rules (a and b)



5. Gravel and Filter Packs

A gravel-packed well differs from a naturally developed well in that the zone immediately surrounding the well screen is made more permeable by removing and replacing the formation material with an artificially graded material. The net effect is to increase the effective diameter of the well. Because the gravel pack specially is intended to prevent migration of formation material into the well, the well screen needs to be centered in the borehole; this centering normally is achieved by the use of centralizers above and below the screen section.

5. Gravel and Filter Packs

5.1 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 D_{10} and D_{60} (often D_{40}). 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 5.1)**

5. Gravel and Filter Packs

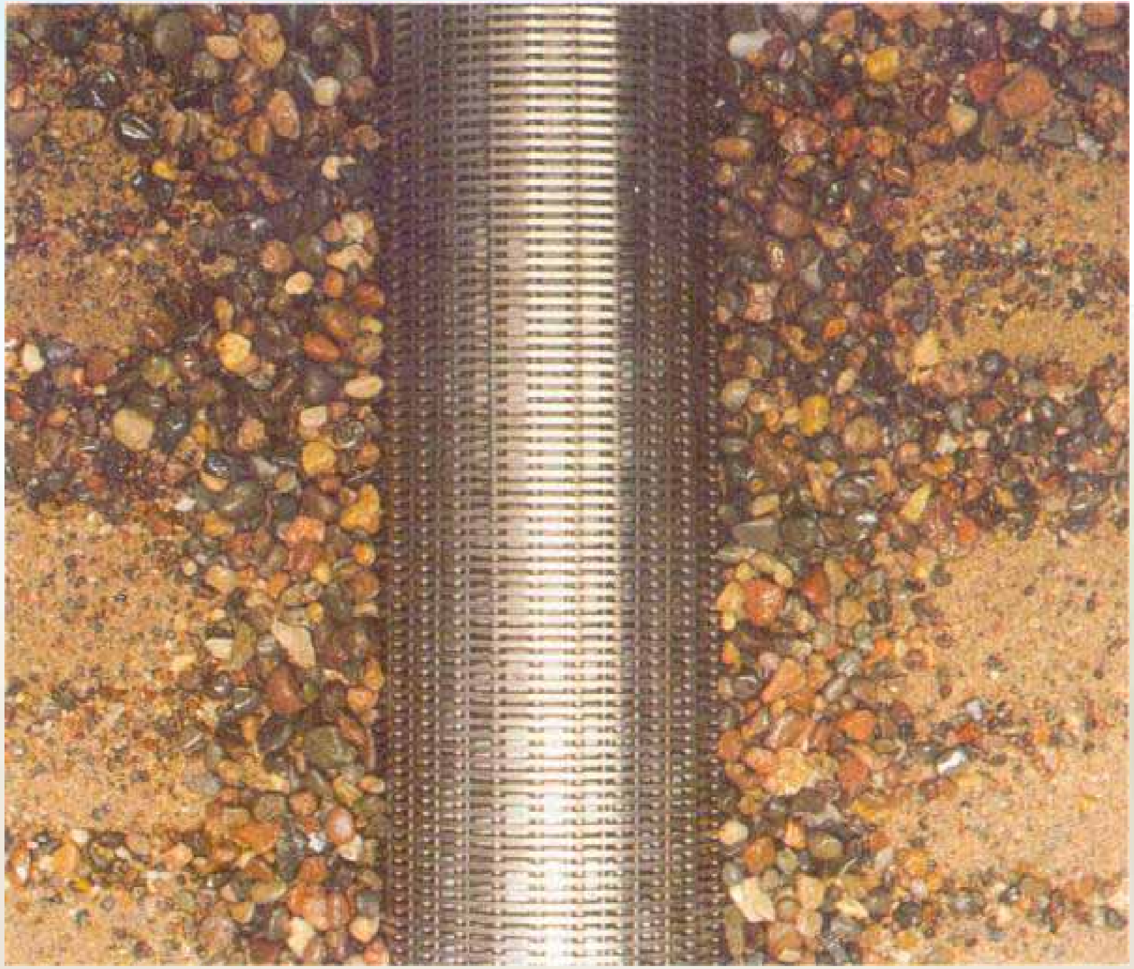


Figure 5.1 Natural development removes most particles near the well screen that are smaller than the slot openings, thereby increasing porosity and hydraulic conductivity in a zone surrounding the screen.

5. Gravel and Filter Packs

5.2 Artificial Gravel Pack

Also known as gravel filter pack (**see Figure 5.2**), 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. Gravel and Filter Packs

The following conditions indicate the use of an artificial gravel pack in well construction:

- ✓ **Fine uniform sand:** the use of gravel pack enables the use of a larger slot size. If the appropriate slot size is less than 0.25 mm, the use of gravel pack needs to be considered.
- ✓ **Thick confined aquifer:** In a situation where a long screen length is needed and the pump is to be set above the screen section, a smaller diameter screen can be centered in the borehole, and the annulus can be filled with gravel. A less preferable solution is to install a shorter screen length that has a diameter about the same size as the borehole.

5. Gravel and Filter Packs

- ✓ **Loosely cemented sandstone:** For a fine-grained sandstone that needs a screen opening of 0.127 mm or smaller, a naturally developed well (based on a 50% passing value) may be used. However, an artificially graded gravel or filter pack may need to be installed to a larger slot size can be used. In addition, a sandstone aquifer frequently provides minimal or no lateral support (i.e. the formation may slump or cave agqinst the screen during development). Hence, some void spaces may remain between the screen and the walls of the borehole and may result in a consequent potential for failure of the casing due to fatigue. Gravel Packing will minimize the possibility of failure.

- ✓ **Finely laminated formations:** in finely laminated formations, the determination of the precise location and thickness of each individual stratum and the choice of the proper length of each section of a multiple-slot screen that corresponds to the stratification is difficult. In this situation, gravel packing enables a more uniform design.

5. Gravel and Filter Packs

5.2.1 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. Gravel and Filter Packs

5.2.2 Gravel Pack Materials

Gravel Pack should be (see **Table 5.1**):

- ✓ 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.

5. Gravel and Filter Packs

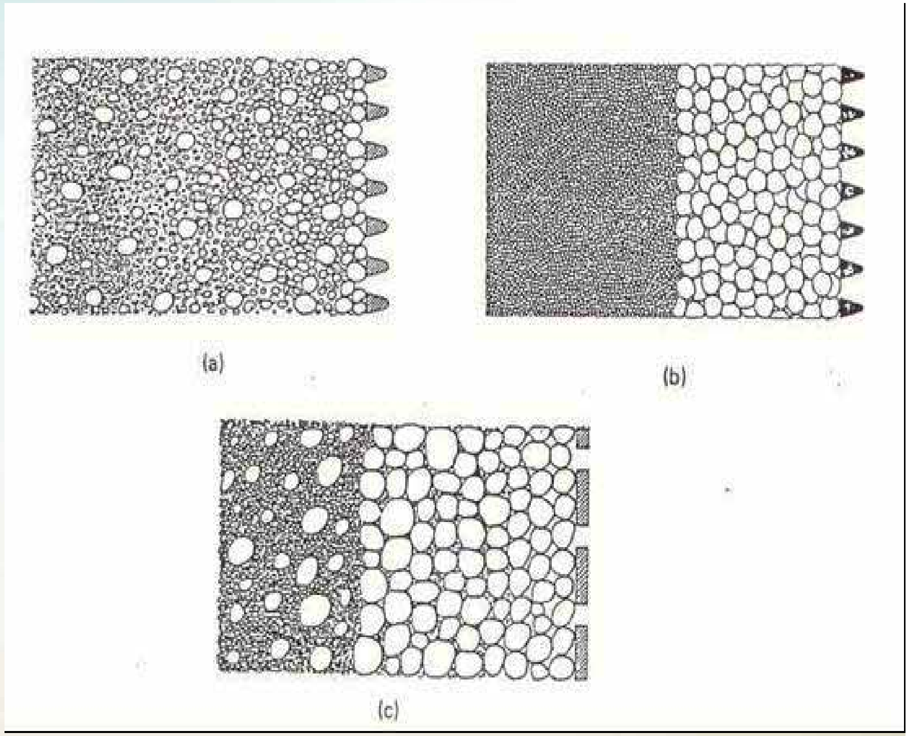


Figure 5.2: The basic differences between the arrangement of the sand and gravel in natural and artificial gravel packed wells. (a) The principle of the natural or ‘developed’ well with each zone correctly graded to the next so that the whole pack is stabilized. (b) An artificial gravel packed well in 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. Gravel and Filter Packs

Table 5.1 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

5. Gravel and Filter Packs

5.3 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 sizs than would otherwise be possible.

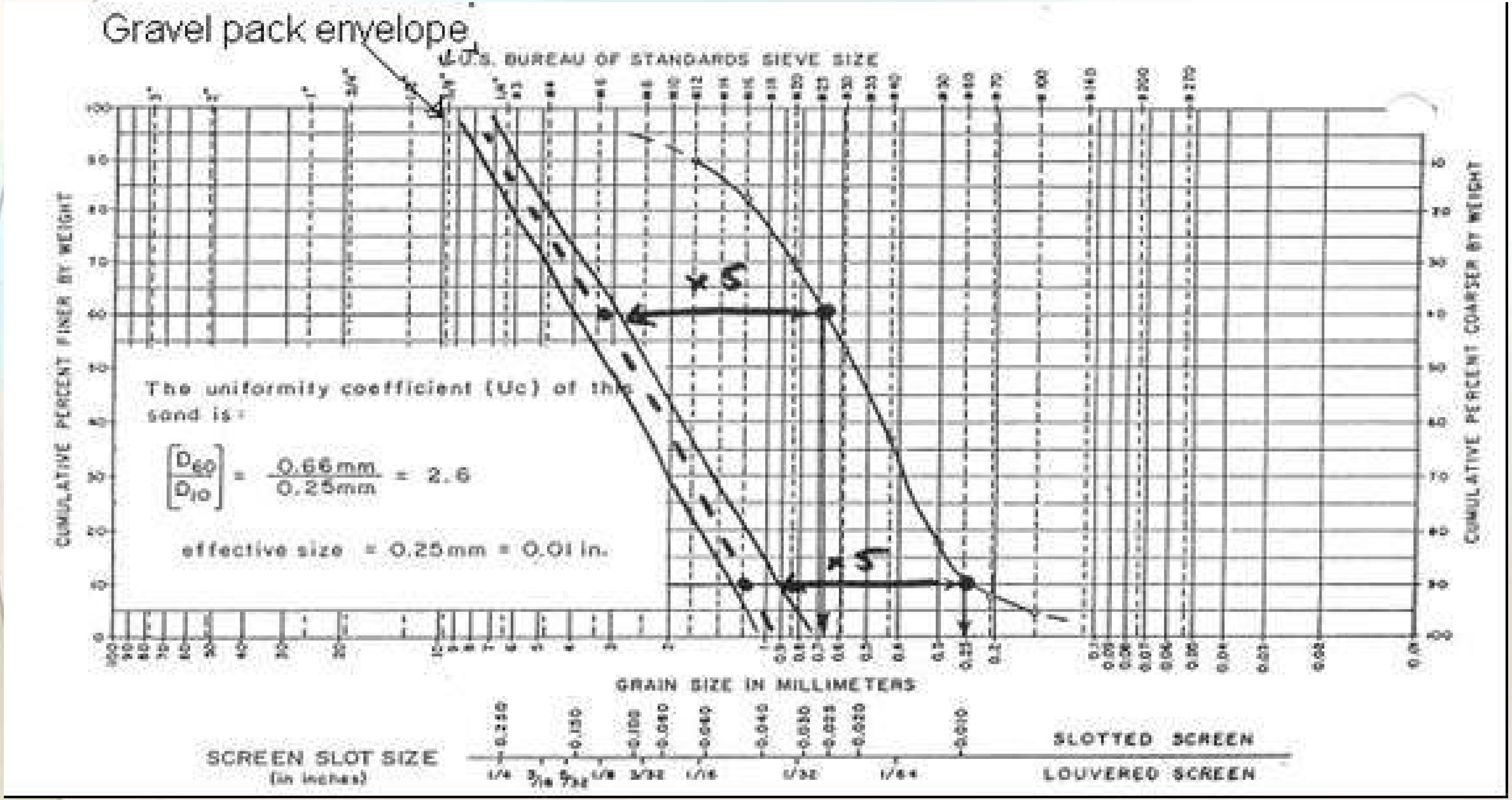
5. Gravel and Filter Packs

Grading

The basic rule is (after Terzaghi, 1943):

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. 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 5.3**)

5. Gravel and Filter Packs



The uniformity coefficient (Uc) of this sand is:

$$\left[\frac{D_{60}}{D_{10}}\right] = \frac{0.66\,\text{mm}}{0.25\,\text{mm}} = 2.6$$

effective size = 0.25mm = 0.01 in.

Figure 5.3: Selection of gravel grading

5. Gravel and Filter Packs

Another approach is based upon the following observations:

- ✓ The pore size of a well graded material is usually about $0.4xD_{10}$
- ✓ The material will be retained if its D_{50} is retained

Hence, if the D_{50} of the formation is larger than $0.4xD_{10}$ of the filter pack, the material will be rtained by the filter pack. The slot size of the screen is then given by the gravel pack D_{85} size. This value is regarded as the maximum theoretically possible, therefore the value is reduced by a safety factor of 2 (see **Figure 5.4**)

Formation grain size should be based upon the finest aquifer material that is to be screened.

The target drading of the gravel pack is specified with an envelope of values into which the actual grading must fall (eg. Plus or minus 10 percent)

5. Gravel and Filter Packs

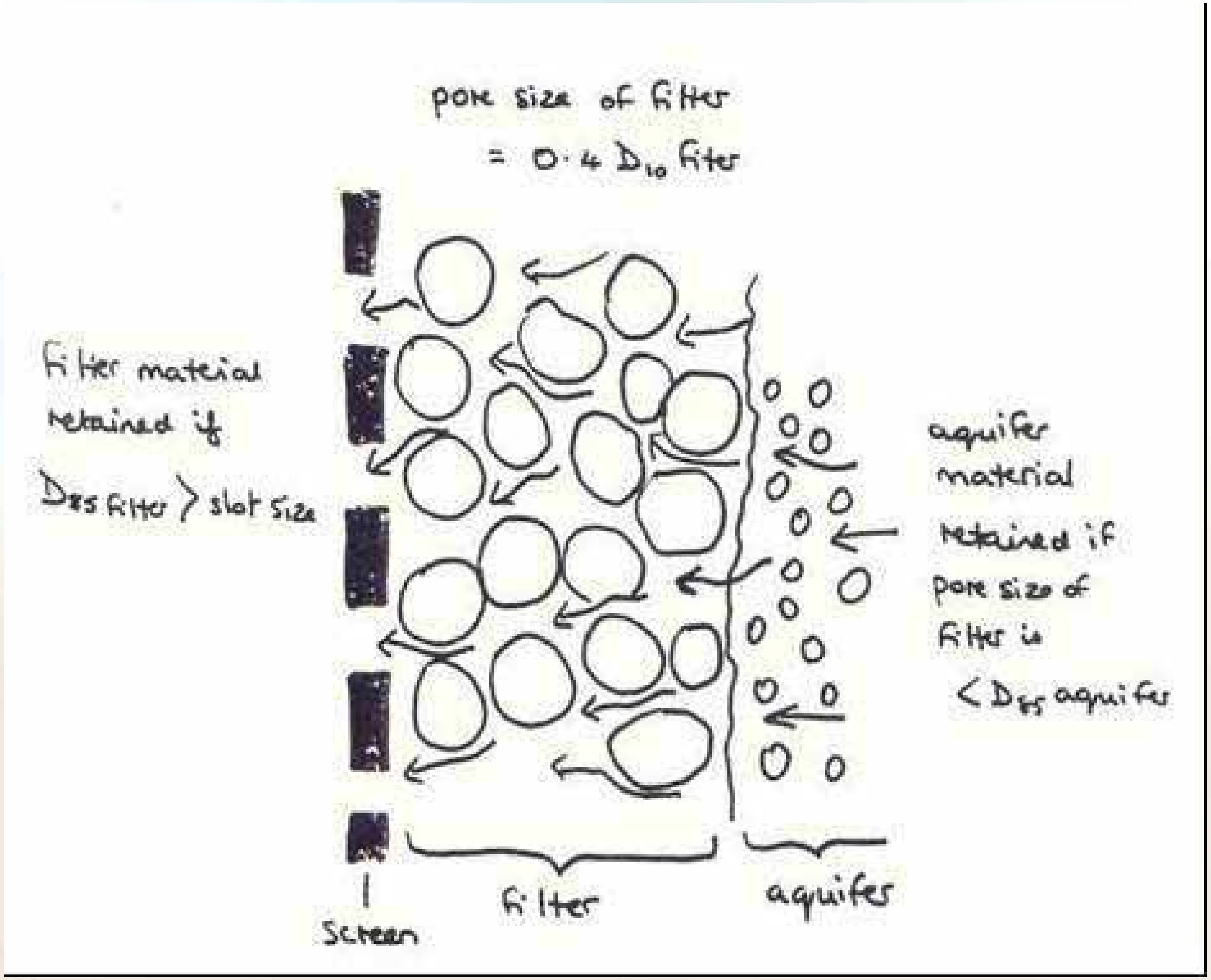


Figure 5.4

5. Gravel and Filter Packs

Example on Gravel Pack Design and Installation

A) (i) Describe the main functions of an artificial gravel pack.

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

Sieve Size (mm)	Mass retained (kg)
2.0	0
1.0	0.24
0.5	0.50
0.25	0.78
0.125	0.30
0.063	0.05
Mass passing through 0.063 mm sieve	0

Construct a grain size distribution curve and confirm that an artificial gravel pack is required. Construct a grading curve for the gravel pack. Suggest a suitable screen slot size.

5. Gravel and Filter Packs

Answers

(i)

- ✓ Prevent of fines in well
- ✓ Increase effective hydraulic radius
- ✓ Supply formation and prevent collapse leading to damage
- ✓ Laterally restrain and effectively strengthening casing

5. Gravel and Filter Packs

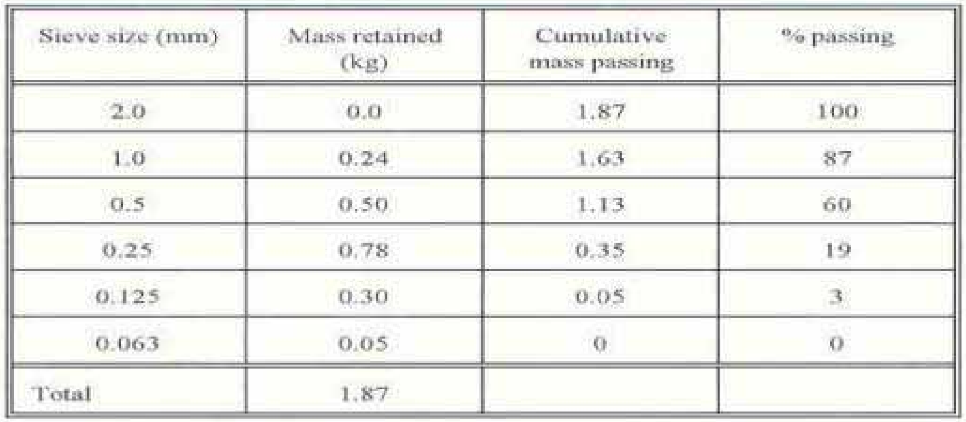
(ii)

Uniformity coefficient = $D_{60}/ D_{10} = 0.5 / 0.19 = 2.6 < 3$.

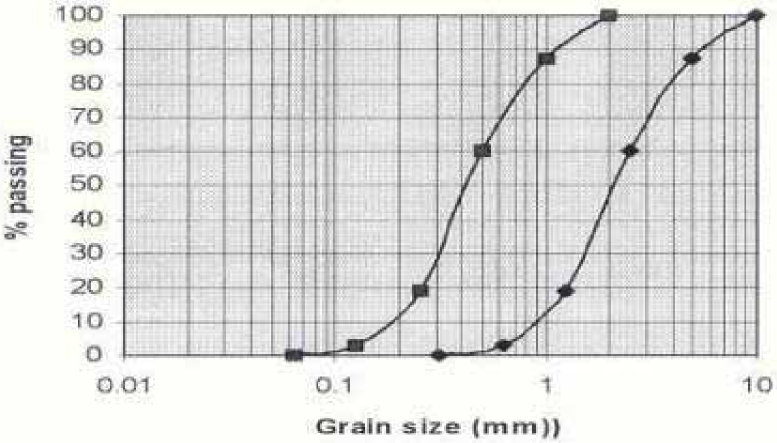
$D_{10} = 0.19 < 0.25$ mm,

so artificial pack required/

Slot size = D_{85} size = 0.9 mm.



Sieve size (mm)	Mass retained (kg)	Cumulative mass passing	% passing
2.0	0.0	1.87	100
1.0	0.24	1.63	87
0.5	0.50	1.13	60
0.25	0.78	0.35	19
0.125	0.30	0.05	3
0.063	0.05	0	0
Total	1.87		



6. Well Field Design

When the volume of water required is greater than can be most economically supplied from a single well, an option is to develop a group of wells to supply the demand. Such a group of wells may be termed a “wellfield”.

The design of a well field involves all the usual problems with designing a well, plus the additional problems of identifying (see **Figure 6.1**):

- ✓ The “best” discharge for each well in the wellfield
- ✓ The “best” method of connecting the wells into the water distribution system
- ✓ The “best” spacing between wells
- ✓ The “best” layout of the wells in the wellfield

6. Well Field Design

The “best” discharge for each well is likely to be the maximum obtainable from a single well, as the usual “economies of scale” obtained from groundwater installations mean that this is close to the optimum solution, in most circumstances.

The spacing of wells, and the layout of the wells, are less easy to provide guides to. Well spacing should be increased to reduce **interference** between wells, but will normally cause the cost of the **connection system** (to carry the water to the point of use) to correspondingly increase. Theory might suggest that a well layout is something like a hexagonal pattern might provide the optimum geometry, but the well-to-well distance would have to be computed from a consideration of the economics of the scheme as a whole, and is an area where optimization can be carefully used.

6. Well Field Design

Other considerations for the layout of the wells focus on the induced flow patterns in the aquifer system caused by the implied large withdrawals of water. This can lead to developing layouts designed to:

- ✓ Intercept a large proportion of the through flow of the aquifer (such as constructing a line of wells across the aquifer);
- ✓ Minimize the adverse environmental impact of the abstractions, keeping development away from sensitive areas;
- ✓ Exploit the unconfined part of the aquifer, to induce more recharge, reduce interference and well drawdowns (and using economies of scale in reducing the cost of transferring water on the surface over long distances).

6. Well Field Design

The problems can quickly become very sophisticated, and demand the use of advanced modelling and optimization techniques.

Connections between the well-head and the point of supply are usually constructed using pipes, but for larger discharges, over long distances, open channel conduits may be more appropriate. The connection pattern is usually to link all wells to a single treatment/storage facility, and the pipe the combined flow into the established water distribution system.

Figure 6.1: Optimum well spacing for a wellfied