DESIGN OF WELL-SCREENS AND GRAVEL-PACKS FOR TUBE WELLS

A Dissertation Submitted
in
Partial fulfilment of the Requirements
for
The Degree of Master of Engineering
in
(Dam design Irrigation Engineering and Hydraulics)

By
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CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF ROORKEE
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CERTIFICATE

Certified that the Thesis entitled 'Design of Well Screen and Gravel Packs for Tubewells' which is being submitted by Sri Pormanand Gupta in partial fulfilment for the award of the degree of Master of Engineering in (Dam Design, Irrigation Engineering and Hydraulics) at the University of Roorkee, is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of about Five and a half months from 15th April 1961 to 25th September 1961 for preparing this thesis for Master of Engineering Degree of this University.

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SYNOPSIS

The aim of this paper is to give a scientific approach to the subject of 'Tube Wells Design'. The primary purpose of good well design is getting the full yield of a water bearing formation. The yield or transmitting capacity of a well, and thus the cost of pumping groundwater, and the amount of water obtained is governed by several factors such as, the geological characteristics of the underground reservoir, the velocity of flow (a function of the aquifer permeability and slope of water table), type of screens and their hydraulic properties, size of gravel and screen slot openings (if it is a gravel-pack well) and the efficiency of the well system and the pumping plant. Since the characteristics of the water bearing formation cannot be altered, the maximum efficiency of a well, for any specific location, will depend on proper design and construction of the well, and the pumping plant. Though many elements are involved in a proper design of well and pumping plant, the proper selection of well screens and gravel envelopes (or gravel-packs) to meet the specific needs and conditions found at the well site, encounters one of the major difficulties. A careless selection of these may often lead to failure of the well.

The selection of well screens and gravel packs, until now, has been based largely on experience and tradition. Proper design criteria are to be established for matching the gravel size, slot size and shape, orientation of slots, length of screens, and the hydraulic properties of well screens, so as to incur the minimum head loss consistent with the required strength of screen and maintaining its sand screening characteristics.

The paper brings out the necessity and the criteria for a proper selection of gravel packs and well screens for the maximum stability of the well and maximum yield. It is felt that with the important part the groundwater development is now going to play these problems concerning the tubewell design have aquired added importance and deserve greater attention. The paper also deals with the model technique developed for the testing of gravel packs, and the laboratory testing as conducted and reported herein, to develop criteria for the selection of suitable gravel envelopes.

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1. GENERAL.

1.01. SCOPE. The increasing demand for Domestic, Industrial and Irrigation water in India, and specially in the State of Uttar Pradesh has now made it necessary to develop the groundwater resources to supplement surface supplies. With the completion of the proposed reservoir schemes of the First and Second Five Year Plans, in the country, not many economical sites are now left for harnessing the rivers for irrigation purposes. Further schemes deep into the Himalayan region are not economically feasible due to the unsuitable geology of the lower Himalayan region, and very costly construction and transport difficulties in the higher ones. However, millions of tons of water between the Himalayas in the North and the Vindhyas in the South, seep silently below our feet every moment towards the sea and within easy reach of us. The State of Uttar Pradesh is very much alive to this situation and has already carried out groundwater development on a large scale.

1.02. The essential feature of the groundwater development is the installation of tubewells and more and more attention will have to be paid towards the effiotical design and construction of tubewells. Field experience is always a major source of knowledge on which development of groundwater is carried out. However, details towards securing greater efficiency can largely be worked out in the laboratory and some of them have been brought out for further implementation in the field.

1.11. INTRODUCTION. The major part of the water used for irrigation in the World flows from its source in rivers, reservoirs or lakes to the irrigated lands in response to the force of gravity. However, there are large areas of arable land in arid regions so situated that available water may not be possible to be brought to them by gravity. Other areas may possibly be reached by gravity but the locations and topography with respect to the water supply may cause this venture a costly proposition. For many of such areas tubewells are the only source provided the geology and hydrology is favourable.

1.12. The idea of State owned tubewells as a means of large scale irrigation in the State of Uttar Pradesh dates from 1931. Regular schemes for such wells were started in 1935. Today about 6000 State tubewells and a large number of private ones are in operation in this State, irrigating extensive tracts of land which were area uncultivated or poorly cultivated for want of irrigation facilities.

1.13. As time rolls on, the number of tubewells in this State and all over the country is bound to increase and large sums of money will most certainly be invested in them. This will naturally impose a heavy responsibility on engineers, who will have to handle public money. If these schemes must yield desirable results, greater importance to the subject of design of these tubewells is apparently required.

1.14. Enough scientific approach has not so far been made in this country on the design of tubewells. A few studies were done in the past by Dr. E.Mackenzie Taylor(51), and Prof. R.S.Chaturvedi(40). However, most of their efforts were made with a view to investigate the effects of tubewell pumping on the sub-soil water-table. Based on the statistical data certain design criteria were recommended by A. Sanghi(14), and K.L. Jain(16). The experimental approach for the design of tubewells was, however, made by Prof. R.S.Chaturvedi(49) and a lot of experiments for the design of Radial and Shrouded tubewells were carried out by him at the U.P. Irrigation Research Station. In absence of the suitable criteria, the design of well screens and gravel packs

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CHAPTER. I

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1.13. There is a basic relationship that exists between the size of screen slot opening, size of gravel used for shrouding, and the size of sand grains of the water bearing formation, for an optimum performance of the well. It is apparent that neither the same size of gravel, nor the same size of slot opening in the screen will suit all the water bearing formations. Design criteria are thus needed for the selection of well screens with openings properly chosen to control the sand, and the selection of gravel packs having a size range correctly related to the grading of the water bearing sand.

1.21. Water Bearing Formations. Formations commonly encountered for groundwater development may be, gravels, consolidated or semi-consolidated sands and gravels, quicksands, clays and shales, and sand stone and lime stone etc. Beds of sand and gravel are usually porous and as much as 30 percent to 40 percent of the volume can be open space capable of transmitting water so that saturated layers of sand and gravel penetrated by wells yield copious supplies.

1.31. Necessity of Well Screens. In consolidated formations where the material surrounding the well is stable, groundwater may enter directly into the uncased well. In unconsolidated formations, however, a well screen is necessary which must serve the dual purpose of freely admitting water into the well and supporting the outside material. Without the screen the water-bearing sand or gravel would collapse after withdrawal of the casing. Also, it is only the well screen that enables the water to enter the well through the whole depth of the water-bearing formation penetrated by the bore.

1.41. Necessity of Gravel-Packing. The basic aim of a good well design is getting the maximum yield of a water-bearing formation. Greater yield can generate greater sand pumping which has to be avoided by the use of a properly selected well screen after obtaining a thorough development of the well. For fine uniform formations, however, gravel-packs (or gravel envelopes) are the most economical methods of keeping sand out of a well. In addition, use of a gravel-pack allows larger screen openings than can be used if the screen is in contact with the aquifer. Large screen openings reduce head loss and also reduce screen encrustations.

1.51. Effect of Sand Pumping. Water-bearing formations capable of supplying water for irrigation wells are usually made up of fine sand mixed with varying amount of coarser material. Since, the discharge from a tubewell is essentially a problem of subsoil flow of water through sand towards the tubewell, the discharge naturally will depend upon the velocity of this subsoil flow. For a large quantity of water the rate of flow through the sand adjacent to the well, has to be relatively high, and if the velocity is high enough to move the sand particles in a particular strata, the water will carry away the sand particles towards the well. Unless provision is made for controlling the movement of sand by means of properly designed screens and properly selected gravel envelopes, excessive quantities of sand can be moved which may ultimately cause the failure of the well. After a failure of this type it may not be possible to salvage even the pump, casing or screen.

1.02. Continued sand pumping may necessitate replacement of the pump because of the wear on the impellers and bowls by abrasive action of sand. Also the pumped sand can sometimes be deposited in the pipe or guls used for conveying the water from the well. Removal of this sand also adds to the maintenance cost.

1.03. The effect of sand pumping upon the life of the well and the life of the pump, is thus quite serious. Lot of money can be saved by a proper selection of well screens and gravel envelopes to prevent the movement of sand particles, and make the wells and pumps last longer. The rate of infiltration of water can thus be safely increased for a greater yield from the well.

1.01. TUBEWELL FAILURES. Most of the tubewell failures in the State of Uttar Pradesh, particularly in the districts of Meerut, Bulandshahr, Muzaffarnagar, and Aligarh, have been traced to following situations :

(1) Excessive discharge of sand
(2) Steady decline in yield over a period of time leading to uneconomical pumping.

1.02. These situations can be analysed to have happended due to one or more of the following causes :

(1) Pitting of Blind Pipe.
(2) Pitting of housing pipe in Borehole
(3) Rupture of plugging
(4) Bursting of strainers
(5) Improper size of screen slot openings
(6) Improper Gravel packs, and their improper development
(7) Choking of strainers.

(8) Corrosion of well screens, and

(9) Failure of the strata surrounding the well screens.

Thus the proper selection of gravel packs and well screens play the major part in the successful working of a tubewell.

DEFINITIONS

1.71. Natural water bearing formations are neither composed of uniform size of sand grains nor do they have their sand grains as perfect spheres. Therefore, for practical considerations the effective size and uniformity coefficient of a water-bearing sand formation are of great importance for the design considerations of a proper well screen and suitable gravel packs.

1.72. Effective Size (or the D_{10} size). The effective grain size is the diameter of the sand grain which has 90 percent of the sand strata sample (by weight) coarser than itself.

1.73. D_{50} - Size. The D_{50} - size is such that half of the material in the sample (by weight) is smaller in diameter.

1.74. D_{60} - Size. The size of particles in a granular material such that 60 percent (by weight) of the material, is smaller.

1.75. Pack-Aquifer (P-A) Ratio. It is the ratio of the D_{50} size of the gravel pack to the D_{50} size of the aquifer.

1.76. A Gravel Envelope or Gravel Pack is a layer of gravel which is placed around the well screen to retard the movement of sand and to allow free passage of water into the well.

1.77. A Well Screen is that portion of a well casing which contains openings through the wall for the passage of water into the well.

1.78. Loss of Head is the loss of potential energy between any two points as measured by the difference in elevation of water surface in piezometers connected to those points.

1.79. Screen Coefficient, C_s, is the ratio of the perforated area of a well screen to the total surface area of the screen, the quantity being expressed as a percentage.

1.80. Uniformity Coefficient, $\frac{D_{60}}{D_{10}}$. It is the ratio of the diameter of a sand grain that has 40 percent of the sample (by weight) coarser than itself to the effective grain-size (D_{10}). The uniformity coefficient of a sample of sand (as defined) is thus an indication of the ratio between the sizes of the larger and smaller grains and in a measure indicates the porosity of denseness of the sand stratum.

1.01. The larger the uniformity coefficient, the smaller is the porosity, and larger the effective grain size the coarser would be the formation. Thus it is better to have a large value of effective grain size and low value of uniformity coefficient for good yield. However, the lowest limiting value of the uniformity coefficient is unity when all the grains are of equal size. Consequently the porosity in such a case will be maximum i.e. 47.64 percent. Uniformity coefficients below 2 indicate nearly 45 percent voids, between 2 to 5 about 40 percent, and between 6 to 8 about 30 percent only.

1.02. <u>Uniform & Non-Uniform Materials.</u> Materials with uniformity coefficients from 1.5 to 2.0 have been considered uniform, and from 3.0 to 5.0 as non-uniform.

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SECTION (1)

(WELL-SCREENS)

CHAPTER. II

WELL SCREENS HYDRAULICS

2. WELL SCREENS' HYDRAULICS.

2.01. **Well Screens.** Well screens are highly specialized types of well equipment and are the most important and at the same time the most sensitive part of the drilled well. They are designed and constructed to secure the highest possible yield from the water-bearing strata into which they are placed. The primary purpose of a properly constructed well screen is not to prevent the entrance of all sand but rather to permit the fine sand to enter so that it can be removed, and to hold out the large particles which may build up into a natural gravel screen around the well tube.

2.11. **Basic Requirements of Well Screens.** The well screens must comply with the following basic requirements

(a) Sand free operation.
(b) Low screen resistance.
(c) Resistance against corrosion and deterioration.
(d) Resistance to stress, and
(e) Be Economical.

2.12. **Sand Free Operation.** The well screen inserted in sand and gravel formations should be of such a construction and design that it always delivers a sand-free water. The well screen is by no means required to be sand-proof but its operation must be sand free.

2.13. Low Screen Resistance. The screen resistance arises from the loss of energy the water sustains during its passage through the well screen. The degree of the screen resistance depends on the design i.e. on the shape and size of the screen openings, the granulation of its gravel pack, the order of depression head created, the quantity of water drawn, and on the velocity of entry. The size and shape of the entry openings and their arrangement are of particular influence and affect the screen resistance most vitally.

2.14. Resistance Against Corrosion & Incrustation. In the soil, well screen and casings are subjected to natural attacks of incrustation and corrosion. These process have different causes and are the result of different chemical reactions, but they cannot always be analysed in the field. All the corrosive attacks of water and soil against the screen material should be successfully countered through a proper choice of material, or alternatively equivalent protection should be reached by the application of suitable coats of enamel, rubber or plastic material.

2.15. Resistance to Stress. Well screens must be built to withstand stresses of certain degrees; of vital importance is the resistance to ground pressure. Furthermore, it should be observed that the well casing reaching from the top of the screen upto the surface of the earth, represents in some cases such a heavy load that the screen, already weakened by the perforation, must be specially reinforced to withstand the pressure without being bent or crushed. Proper selection of the wall thickness with a proper spacing of the perforation is the basic condition for building up the resistance to stresses on the screen.

2.10. In addition to these requirements, as a matter of course, the costs of purchase and installation of the well screens should be kept as low as may be compatible with maximum service life of the filter.

REVIEW OF LITERATURE

2.21. Suggested Criterions. Since there are few investigations of well screens, the selection of a proper screen has been a matter of engineering judgement and experience. A criterion proposed by E.W.Bennison(47) in 1939, is that a velocity of less than 0.1 ft. per sec. through the individual screen openings, will keep sand movement and head losses to a minimum. He suggested that :

(1) The screen should be such as not to hold out all or a large part of the formation around it but rather to work as a device to support the water-bearing formation during the development and subsequent pumping.

(2) The screen openings should be relatively large and based on an intelligent interpretation of the sand analysis and local ground conditions.

(3) The screen should have as much opening and as little blank space as possible in order not to shut off the natural openings in the water-bearing formation.

2.22. [illegible](7) in 1942 reported that a screen with a high coefficient of capacity C_n, (defined as the ratio of the area of slot openings in a screen to the total area of the outside surface of the screen) is desirable. He stated that this coefficient multiplied by the original porosity of the aquifer, will give new porosity of the aquifer.

2.23. [illegible](30), in a study, pointed out that the loss of head through a well screen consists of two distinct and separate parts. There is a loss of head through the screen openings due to their size and shape and there is another loss of head attributed to the turbulence of the water in passing upward through the inside of the well screen. The sum of these two losses is the loss of head in bringing the water from outside the well screen to the pump. The loss of head through the screen openings may be written in the form of a velocity head loss :

$$h = K \frac{V_2^2 - V_1^2}{2g} \qquad (1)$$

where h = the loss of head through the screen openings in feet.

V_2 = the velocity of water at exit through the openings.

= Q/A where Q is the discharge in cft. and A the area of openings in sq. ft.

V_1 = the velocity of water at entrance to the screen openings.

= Q/A_o where Q is the discharge and A_o the outside area of the well screen.

K = a coefficient varying with the roughness of the screen and the temperature of the water.

g = acceleration due to gravity.

2.24. The loss of head due to turbulence and friction inside the screen may be written in form similar to the equation for the loss in a pipe:

$$H = f \frac{V^2}{2g} \frac{L}{D} \qquad (2)$$

Where H = The loss of head in the pipe in feet

V = The velocity of flow in pipe in ft/sec.

L = The length of pipe in feet.

D = The diameter of pipe in feet.

g = The acceleration due to gravity.

and f = a coefficient varying with the roughness of the pipe.

2.29. Gilbert Lee Corey(7) in studying the hydraulic properties of well screens, worked out the relationship between the screen coefficient (defined as the perforated area divided by the total surface area of the screen), and the loss of head through the screen. He established that when the screen coefficient is about 15% or greater, it has little or no effect on the loss of head through the screen. Below 15% there is a sharp rise in the loss of head as the coefficient decreases. Thus if a screen has sufficient perforated area the loss of head is practically independent of the shape of the openings.

2.30. When the value of screen coefficient becomes less than 15%, the water must pass through the slots at a greater velocity because of the reduced perforated area. If this velocity is great enough a significant loss is likely to occur. With increased velocity the momentum of the jets is increased and a greater amount of energy is dissipated in deflecting the jets through 90°, leading to a greater head loss inside the screen.

THEORETICAL DEVELOPMENT OF FLOW THROUGH WELL SCREENS.

2.31. The hydraulics of a well is a fascinating subject. Like all other engineering Sciences, however, it is not an exact science and the mathematical assumptions which often have to be made represent only limiting cases of real conditions. The well hydraulics involves flow (1) in the surrounding aquifer, (2) through the well screen, and (3) inside the well.

2.32. The problem of flow into and through well screens can be considered to be one of flow through a series of orifice openings as the water enters the screen and flow within a pipe manifold as it moves along the axis of the screen. As the water enters the screen through the openings, a conversion of potential energy to kinetic energy is necessary to develop the jet velocity. A dissipation of the jet energy, which can be assumed to be complete, then occurs, i.e. the kinetic energy of the jet is not recovered as either potential or kinetic energy. The water then accelerates in a direction parallel to the centre line of the screen. The acceleration results in a change of the momentum flux. As a first approach, considering the analysis for a screen, surrounded only by a liquid, the loss of head caused by flow through the well screen in that case, will depend on the characteristics of the screen geometry, the fluid, and the flow. The variables of greatest importance involved in the problem are :

(1) The screen length L.
(2) The screen diameter D.
(3) The percentage of open area Ap.
(4) The coefficient of contraction for the screen openings Cc,
(5) The internal roughness of the well screen K
(6) The difference in pressure between the inside and the outside of the screen Δp.
(7) The velocity of the liquid in the well screen V.
(8) The mass density of the fluid ρ ; and
(9) The coefficient of dynamic viscosity μ .

These variables can be expressed in the following relationship :

$$f_1(L, D, \Delta p, K, \rho, \mu, V, A_p, C_c) = 0 \qquad (3)$$

If D, ρ and V are chosen as repeating variables, a dimensionless analysis will yield the function :

$$f_2\left(\frac{L}{D}, \frac{K}{D}, A_p, C_c, \Delta p / \rho V^2, VD\rho / \mu\right) = 0 \qquad (4)$$

2.33. The parameter ($\Delta p / \rho V^2$) can be written as ($\Delta h / \frac{V^2}{g}$) if multiplied by (γ/γ) , where γ is the specific weight of the fluid and Δh the difference in piezometric head between the pressure inside and pressure outside the screen.

2.34. Since the effects of viscosity are of secondary importance, the Reynold's Number can be eliminated. Further more since, the drag inside the well screen is almost entirely the result of the influence of the jets issuing from the screen openings, the roughness parameter can also be neglected, thus

$$\Delta h / \frac{V^2}{g} = f_3 \left(Ce,\ Ap,\ \frac{L}{D} \right) \qquad (5)$$

2.35. Applying the principles of continuity, energy and momentum and assuming

(a) No acceleration to the direction of flow.

(b) No variation in the velocity across the sections considered and

(c) No resistance to flow,

a dimensionless relationship can be obtained in the form :

$$\frac{\Delta h}{V^2/2g} = 2 \left(\frac{\cosh \frac{cL}{D} + 1}{\cosh \frac{cL}{D} - 1} \right) \qquad (6)$$

which combines the dimensionless parameters, Ce, Ap, and $\frac{L}{D}$, into a single variable.

Here V is the final average velocity along the vertical axis of the screen, and Δh the difference in piezometric head between the outside and inside of the screen and C is defined as :

2.36. $$C = 11.51 \cdot Ap \cdot Ce. \qquad (7)$$

The two dimensionless numbers involved in the equation, ($\Delta h / \frac{V^2}{2g}$, & $\frac{CL}{D}$) can be plotted to give a theoritical curve. As shown by the curve, the loss coefficient $\left(\Delta h / \frac{V^2}{2g}\right)$ becomes nearly constant when the hyperbolic cosine of ($\frac{CL}{D}$) is large, so that the plus or minus 1 is insignificant. Since the loss coefficient is a measure of the loss the loss is a minimum when the parameter is a minimum. The loss coefficient ($\Delta h / \frac{V^2}{2g}$) approaches a value Two, for values of ($\frac{CL}{D}$) greater than SIX.

2.37. The value of ($\frac{CL}{D}$) depends only on the characteristics of the screen. A larger value of ($\frac{CL}{D}$) than the critical value of SIX, can be obtained by,

(a) increasing the length of the screen.

(b) increasing the percentage of open area A_p.

(c) improving the shape of the openings in such manner as to increase the coefficient of contraction.

Decreasing the diameter of the screen also increases the value of $\frac{CL}{D}$, but it reduces the capacity of the well.

2.39. Equation No.6, and figure No. 2.36, indicate that the performance characteristics of a screen are not improved by ($\frac{CL}{D}$) values greater than SIX. This is important because additional lengths of screens are costly. This theoritical development for flow through well screens, was postulated and experimentally confirmed by Jack.S.Petersen(2).

2.41. When the screen is surrounded by gravel, several additional factors enter the problem. These factors include the size of the openings in relation to the size of the gravel, the size of the gravel relative to the diameter of the screen, and the standard deviation of the gravel.

2.42. With gravel envelope around a well casing, a new constant—C_p, the coefficient of the perforated casing, has been defined by Peterson et al(2). The coefficient is the product of the coefficient of contraction (C_c) and the fraction of open area remaining open upon partial plugging by gravel ($\frac{A_a}{A_p}$), where A_a is the percent of open area when gravel surrounds the casing and A_p the percent of open area without gravel.

By definition then, $C_p = \frac{C_c . A_a}{A_p}$ (8)

2.43. With no gravel around the perforated casing, A_a is equal to A_p and C_p is equal to C_c.

2.44. Equation No.7 developed for analysis without a gravel envelope, defines C, (in the term $\frac{CL}{D}$), as $11.31\ A_p . C_c$. The term $A_p . C_c$. is the effective area of the openings. With gravel around the perforated casing, A_p no longer applies, and $A_a . C_c$. expresses the effective open area under this condition. Writing $A_p . C_p$ for $A_a . C_c$, which are the same according to equation No.8, it can be obtained, as :

$$C = 11.31\ A_p . C_p . \qquad (9)$$

2.49. Equation No.9 is a general equation, describing conditions whether or not gravel surrounds the casing.

HYDRAULIC HEAD LOSSES OF WELL SCREENS

2.51. On the basis of the analogy of flow of water through a well screen to flow through a series of orifices, a straight line relationship between hydraulic head loss and rate of flow can be obtained. Hydraulic head losses in orifice flow may conform to the equation

$$\Delta h = \left(\frac{1}{C_v^2} - 1 \right) \frac{V^2}{2g} \qquad (10)$$

where Δh is the hydraulic head loss, C_v the coefficient of velocity and V the jet velocity.

2.52. Taking the logarithm of each side and substituting $V = \frac{Q}{A}$ gives -

$$\log \Delta h = \log \left[\frac{\left(\frac{1}{C_v^2} - 1 \right)}{2g} \right] + n \log Q - n \log A . \qquad (11)$$

which indicates a straight line relationship between hydraulic head loss and rate of flow.
The slope of this line is equal to n and its intercept is

$$\log \left[\frac{\left(\frac{1}{C_v^2} - 1 \right)}{2g} \right] - n \log A . \qquad (12)$$

2.53. The magnitude of the slope will not change as long as the characteristics of the openings are such that its drag coefficient is independent of the Reynold's Number of the opening. The intercept of the line may, however, change with variations in the value of Cv or of the open area. At low values of Reynold's Number of the opening, viscous effects will tend to reduce the value of Cv slightly, but at high values Cv may be considered to be constant.

2.54. Any appreciable variation in the value of the intercept is caused by changes in the open area through which with flow occurs. This is of great importance as it shows that one of the major factors controlling the magnitude of head losses per unit flow is the value of the open area.

2.61. _Factors Controlling the Open Area._ The open area of well screens can be controlled in several ways. The simplest is to provide a greater number of openings per unit area, but loss of screen strength limits this approach. Another way to increase the effective open area of the openings is to increase the coefficient of contraction by improving the shape of the openings. For sharp edged slots, it has been shown that the value of Cc is $\frac{\pi}{\pi+2}$ or 0.611(64), thus flow occurs through only about 0.6 of the opening.

2.62. The range of values of Cc is affected by several factors, including (a) Orifice edges,

(b) Thickness of edges; and

(c) Orientation of mouth of opening to direction of flow.

The first two factors, roughness and thickness, tend to increase Cc and decrease Cv. An increased value of Cc may be offset by a decreased value of Cv. The highest Cv value is obtained with smooth relatively thin openings. With opening of this nature Cv varies only slightly with Reynold's Number and for all practical purposes remains constant.

2.71. The well screens are thus required to meet the several basic requirements. These requirements complicate the matter of selecting the well screens. A screen with a large percentage of open area will provide a low resistance to flow into the well, but it will have less structural strength and may permit more pumping of sand than a screen of smaller percentage of open area. The design of an efficient screen will thus, necessarily involve a COMPROMISE.

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CHAPTER. III

TYPES OF WELL SCREENS AND PERFORATIONS

3. TYPES OF WELL SCREENS

3.01. So many types and such a wide variety of well screens are produced that it is difficult to form a reliable opinion of their value and their suitability for specific water and ground conditions. Broadly speaking, two types of screens can be distinguished according to whether the retention of the sand is effected by mesh or gravel packing and accordingly they are known as Mesh Screens, and Gravel packed-screens respectively. Depending, however, on their specific use and performance, the well screens may be divided into four classes :

(1) Slotted pipes, perforated well casings, or gravel-packed screens.
(2) Screened well casings.
(3) Continuous slot screens, and
(4) Strainers (or mesh screens).

3.11. Slotted Pipes or Perforated Well Casings

Though functionally the same, a distinction is usually made between the slotted pipes (or perforated well casings), and the screened well casings, depending upon their construction and specific use. Slotted pipes are used in conjunction with gravel packs in the alluvial aquifers where the sand is relatively finer. In such aquifers most of the sand which will move is usually carried out of the well in the development process.

3.19. Slotted Pipes. The slotted pipes are desirable where in a given depth of boring a sufficient strata for the required length of strainers, is not available. The open area of slotted tube in comparison with strainers area is usually of the order of 1/2 to 3/8, but as the effective diameter due to gravel packing is about five times with a slotted pipe, the net result is that the required tube length is half that of the strainer length. Thus for a 100 ft. length of strainer, the equivalent length of slotted pipe will be about 50 ft. only.

3.13. To take an example, if in a depth of 300 ft. of boring only 50 ft. of water-bearing strata is available and if it is not desirable or if it becomes prohibitive to bore further, 6-in slotted tube 50 ft., in length if developed, would give as good a result as 100 ft. of strainer in 100 ft. of aquifer would give.

3.21. Screened Well Casings. The screened well casings are similar in construction as the slotted pipes, but the slots are usually thinner, sometimes forming a close mesh, for use in sandy aquifers to prevent excessive sand movement into the well.

3.31. *Continuous Slot Screens.* The continuous slot screen differs greatly from all other types of well screens. It is constructed of a narrow ribbon of metal wound spirally around a skeleton of longitudinal rods, each point of the contact of the ribbon and rods being electrically welded. It gives the highest percentage of open slot area possible in well screens.

3.41. *Strainers.* A well strainer differs from a perforated or a screened well casing, in the sense that it consists of a wire gauze screen wrapped round a slotted or perforated pipe or a tubular frame with a small annular space between the two, so that the wires of the screen do not mask the slot openings.

3.42. In cases where deep water bearing stratum (relatively coarser) is available the choice of the length of screen is unrestricted and within required limits length can be chosen to suit, and a strainer type of tubewell results. Out of the many kinds of strainers, *Ashford*, *Brownlie*, *[illegible]*, *Tej*, and *Agricultural*, etc. in common use, it had been found that Tej and Agricultural type of strainers were durable. Recent experiments have, however, shown that they too are defective and need much improvement.

3.43. The proper design of a strainer requires that :

(1) It should consist of one metal and should not be bimetallic.

(2) The slit width or strainer opening size should be

  (a) less than the statistically average diameter of the particles of the strata.

  (b) less than the grain size present in largest proportion unless it be one of the smaller sizes.

  (c) such size which on development of well provides a 30%-40% retention i.e. slightly less than D_{60}-D_{70} size.

(3) The slits should be arranged such that the particles creeping up from one slit have freed themselves from the tube surface, before reaching the next slit.

(4) The shape of the slits should provide stream line flow and least resistance to flow of water.

(5) The slit should be bevelled towards inside so that a sand particle after being sucked inside the strainer with water may have the least possibility for clogging the opening and may be taken away by the water easily.

SCREEN PERFORATIONS

3.51. Size of Perforations. The number, size, type, and distribution of perforations or slots can practically control not only the capacity of a well but also determine the life of a well and the wear on pumping units. If the perforations are too fine unnecessary entrance friction is developed which causes greater drawdown and greater pumping lift thereby increasing the cost of operation.

3.52. When the perforations are too large, the maximum amount of water will have free entrance to the well but difficulty will be encountered in inflow of silt, sand and the smaller gravel particles. The sediment may come into the well faster than it is pumped out and partially fill the well shutting off good water-bearing formations. If too much material is pumped out from around the casing, there is the danger of collapse.

3.53. The size and shape of a perforation (or the slot opening) also play a very important part in development work as some formations cannot be developed at all without jamming the screen openings or perforations with sand or else allowing too much sand to pass into the well.

3.54. The size or width of slot openings is naturally contingent upon the formation to be screened. If drilling samples are taken and logged as the well is drilled a satisfactory size of slot opening may be selected. In the older theory for the selection of the size of slot openings, it was thought that the more sand is held out the better. Today just the opposite is true, and screen openings are now selected that will let as much as 80%(11) of the formation into the well.

3.60. Where the heterogeneous alluvial formations contain most of the water, it is commonly considered that the size of perforations should be chosen so that about 60%(33) of the grains will be passed through openings and about 40% of the grains will be retained outside the casing. As the finer material is pumped out of the well, the larger grains settle around the casing forming an envelope area with greater porosity and larger passages for transmission of water into the well.

3.61. Types of Perforations. Depending upon the mode of their construction the screen perforations may broadly be divided into two classes :

(1) Machine perforations which are cut in the factory.

(2) In-place perforations made by perforating machines while the casing is in the ground.

3.62. Machine Perforated Casings. Where it is possible to use machine-perforated casing it is much more satisfactory than casing ripped in the well by perforating machines. The slots in the former are correctly spaced and all of the uniform desired size. The casing is not weakened measurably by the perforating, as is likely to be the case when ripping is done in the hole. The perforated pipe can be placed opposite the desired point and can be depended upon to exclude all of the sand with a diameter greater than the specified slot.

3.63. *Casing Perforated in the Ground.* With these casings, it is difficult to control satisfactorily the size and spacing of the slots made by the perforating machine. If a pumping test indicates incomplete perforation, a second use of the cutter will probably result in over perforation and is almost sure to tear or rip the casing. In many cases old casing has been pulled from wells in which holes as big as a man's first were torn by faulty action of the cutter blades. Such oversize holes may cause collapse of the well soon after its completion.

3.71. *Shape of Perforations.* The shape of perforation governs the hydraulic properties of well screens and the sand clogging characteristics. Assuming the sand grain to be spherical in shape it will touch all round its periphery when locked in a round hole. In the case of elliptical hole it will be held at a number of points while in a square hole, it will be held at four points. In the case of triangular hole, it will be held at three points only. In cases of rectangular slots the sand particles will be held only at two points except at the ends where it will be held at three points.

3.72. In continuous slots, however, any sand particle will be at only two points every where. Thus a well screen with a continuous slot opening will offer the least possibility for the screen slots to get clogged.

3.73. The openings in screens having continuous slots are designated in thousandths of an inch and the equivalent gauge numbers are shown in the figure. Thus No.6 means 6/1000-inch and No. 125 is 125/1000-inch or 1/8-inch etc. However, since continuous slots may not always be possible, the rectangular slots are the next most suitable for the well screen design.

3.74. Depending upon their hydraulic proportion, the rectangular perforations can further be divided into the following types :

(1) Punched, straight cut, straight sided, or plain.

(2) Chiselled.

(3) Special types e.g., Bridge slotted perforation & Louvre, and Cage types.

3.75. Punched Perforations. In this type of perforation a grain of sand in order to pass into the well must pass through an opening with parallel sides equal to the thickness of the metal used.

3.76. Chiseled Perforations. In this type, one which is constructed with a sharp outer lip and an abruptly widened inner opening is known as chiseled outside. This will prevent any grains which pass the outer lip from wedging and clogging the opening. The reverse type in which the outer portion is widened is known as chiseled outside and from the standpoint of controlling the passage of sand it invites clogging on account of its reversed V-opening.

3.77. Bridge-Slotted-Perforations. The bridge slotted perforation is the latest type of perforations. In this system the respective orifices are not entirely punched out, but the material is only pressed to protrude to a certain extent, thereby forming small bridges with lateral longitudinal slots. The space between the underside of these bridges and the exterior wall of the tube is called the bridge slotted opening. The bridge slotted perforation has many advantages as compared with the well screen with simple perforations, and the author found in Germany that this type of well screen has introduced itself almost everywhere and dominates now the field of well screens.

3.70. Advantages of Bridge-Slotted Perforations.

The advantages of screens with bridge-slotted perforations are manifold :

(1) Low Screen Resistance. The openings formed by the bridge slots cannot become clogged or displaced by the grain of the graded gravel as in plain perforations, and thus is favourable for keeping the screen resistance low.
(2) Better Stability. The pressed bridges of the bridge slotted well screens offer considerably better resistance to compressive, tensile, and buckling stress.
(3) Greater Rigidity. Owing to the fact that the bridge slots are placed on the outer surface of the filter tube, the whole screen body gains in rigidity.
(4) In the manufacture of bridge-slots, finer slots can be produced even with thicker walls, than is possible with the simple slot perforation. The width of the slots of the latter is always dependent on the thickness of the wall.

The bridge slots can be adapted to the different requirements of the gravel packing and also to the grain size of the water bearing strata, however, the larger is the bridge opening, the deeper is the penetration of the pressing tool into the material, and accordingly the larger the slot length.

3.70. "Shade" and "Louvre" Perforations. The other types less frequently used are the "Shade" and "Louvre" perforations. The Garde perforations is characterized by rectangularly knocked out sections of the tube-walls pressed outwards, each forming a kind of roof thereby preventing very efficiently the clogging of the entry openings through the grains of the gravel packing. The louvre perforation has long lips pressed outwards, running parallel to the filter axis. The width of the entry slots can be dimensioned according to requirements.

3.01. Special-Type Bridge Slotted Perforations. This type of perforation is similar in construction as the ordinary bridge slotted perforations but it meets the essential requirements of screens for groundwaterlowering. There is a basic difference in the screens used for lowering the groundwater as compared with the purpose of supplying water. In the latter case the main object is to secure large quantities of water at a minimum loss of level height, whereas the aim of groundwater lowering is a maximum/sinking of the level.

3.02. The screens for lowering groundwater are subjected to considerably higher stresses and the conspicuous features are chiefly all the high requirements of compressive resistance and buckling strength, and also of the resistance of the screens body against compression. The screens for lowering of the groundwater should, therefore, always have an adequate thickness of wall for providing the high resistance against stresses, and the special type bridge slotted perforations provide the low screen resistance needed for such screens.

3.09. In Uttar Pradesh, the slotted tube is made out of M.S. pipes and the usual design of slots in 6-in pipe is 6 slots 2 in x 1/8-in circumferentially and 12 slots per foot vertically i.e. 6x12 = 72 slots per foot. The slots can either be horizontal or vertical depending upon the type of screen and its specific use. A recent study of "The comparison of the efficiencies of slotted screens with horizontal and vertical slot arrangements", conducted by the author(63) at the Irrigation Research Institute, Roorkee, has indicated a greater sand displacement with vertical slots as compared to the horizontal ones when experimented upon without gravel packing. With gravel packing, there was no problem of sand displacement. The discharges pumped out with horizontal slots, however, were found to be 3 to 6 per cent lesser both when experimented upon with or without gravel packing. It has been suggested that in a slotted pipe tubewell with proper gravel packing slotted pipes with vertical slots, should be used for a greater discharge, and for screened or strainer wells where no gravel packing is done, screened pipes with horizontal slots may better be used, for a greater stability of the tube-well.

3.02. The problem of selecting an ideal well screen is, therefore, one of selecting a screen :

(a) With openings that would provide the maximum amount of open area consistent with strength and the grading of the formations.

(b) A screen which by its design and shape and type of openings would lend itself to the surging and development work necessary to bring the screen to its maximum transmitting ability and at the same time be free from clogging or jamming.

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CHAPTER. IV

CHOICE OF SCREEN DIMENSIONS

4. CHOICE OF SCREEN DIMENSIONS.

4.01. Screen Length. Correct length of the well screen has much to do with good construction and performance of a completed well. If the screen is too long, the cost of the well is increased unnecessarily. If it is too short the yield of the well may be unsatisfactory. The screen must be long enough to take in the major portion of the most permeable strata penetrated by the well. Each section of screen exposed in the differing strata must have the right size of slot openings to permit proper development of each level.

4.02. Factors Affecting Screen Length. The factors that affect the choice of the screen length are:

(1) Open area per foot of screen.
(2) Character of the water bearing formation.
(3) Cost of the screen.
(4) Desired yield from the well.

The selection is often a compromise between the factors of cost and hydraulics.

4.11. Calculations Based on Screen Inlet Area. Maximum open area per foot of well screen reduces the resistance to flow into a well and insures minimum "entrance losses" under any given set of conditions.

For calculating the total open area of the screen (or the screen capacity), a velocity of 0.1(11) foot per second for the water moving through the screen openings has been found to be a good basis for well design. The screen capacity, calculated on this basis, should be in excess of the pumping rate to provide a sort of factor of safety in the event of any gradual reduction of screen openings by mineral deposition over a period of few years.

4.12. Taking an example of the yield of 12,000 G.p.h.(0.44 cu.ft. per second) from a particular water-bearing formation, a screen with a total of $\frac{.44}{0.1} = 4.4$ square feet or 634 square inches of openings should be used. Allowing for 20% extra, the total open area of the screen should be about 800 sq. inches. Dividing this total area by the open area per foot of screen will give the screen length required.

4.13. If it is supposed that the sand of the water bearing formation requires a screen with (0.020 inch) slot openings, and if a six-inch diameter continuous slot well screen is to be used, the screen with 0.02 inch slot openings, will have 30 square inches of open area per foot. Thus, a length of $\frac{800}{30}$ = say 30 feet, would be required.

4.19. The 20 ft. screen length in this example is for a continuous slot screen. A screen of different design with a lesser open area per foot would have to be longer if the velocity is to be kept down to the value assumed. Thus a screen with 20 square inches of open area per foot would have to be 32 feet long to provide an intake capacity of 12,000 g.p.h.

4.20. This might be taken as a "First Estimate" of the screen length. In this estimation only the hydraulic characteristics of the well screen have been considered, and none of the physical or hydraulic characteristics of the water-bearing formation have been taken into consideration except that the size of the slot openings are assumed to fit the grading of the sand.

4.21. _Effect of Formation Thickness_ The thickness of the water bearing formation, the arrangement of fine and coarse layers and the static water depth must all be seriously considered when choosing the screen length. These factors often overrule the calculations made on the basis of screen openings alone. For example, suppose the formation is only eight feet thick but calculations based on screen area indicate a 10 foot screen length, then the aquifer thickness will govern since the 10 foot length cannot be exposed in an eight foot sand.

6.31. Effect of Confined and Unconfined Groundwater

Groundwater occurs in sand formations under two conditions - artesian and water table. An artesian condition exists where the aquifer is capped by a tight formation which confines the groundwater under pressure. A water table condition occurs where only a portion of the total thickness of the sand is saturated. The water is confined and the upper surface of the water in the aquifer is under only atmospheric pressure. The best choice of screen length differs with each of these conditions.

6.32. In a confined or artesian aquifer upto about 30 feet in thickness and where the sand is about the same grading from top to bottom, the length of the well screen should be such as will take in 70 to 80(8) percent of the thickness of the formation. This general rule assumes that maximum yield with minimum drawdown is desired.

6.33. In a water-table aquifer, the length of the well screen can seldom exceed 50 percent of the saturated depth when the saturated portion is between 10 and 50 feet thick.

4.41. Effect of Available Drawdown. The term "Available Drawdown" means the depth from the static level to the top of the well screen and assumes that when well is pumped the water will not be pulled down below the top of the screen.

4.42. The shorter screen gives more available draw-down but it cuts down the efficiency of the well and reduces the specific capacity (g.p.m. per foot of draw-down). Since total yield equals available drawdown multiplied by specific capacity, the problem is to choose the screen length that will make the product of these two factors a maximum. Hydraulic theory and experience has shown that this result is obtained when the screen length is from ⅓ to ½(3) the saturated thickness of the formation.

4.43. In general, the water bearing sand is, however, not of the same grading from top to bottom and most aquifers are stratified that is they consist of different layers of fine sand, coarse sand, and sand and gravel. In such cases the general rules do not apply. The log and sand samples from formation that are stratified must be carefully considered when selecting the best screen length. The screen must be long enough to take in the major portion of the most permeable strata penetrated by the well. Each section of screen exposed in differing strata must have the right size of slot openings to permit proper development at each level.

4.01. <u>Calculations Based on Assumed Yields</u>. As per Dupuit's expression(22) for discharge for unconfined flow, the discharge across a cylindrical surface of radius x is given by :

$$Q = -K \frac{dD}{dx} \cdot 2\pi \cdot x\,(L + D - h) \qquad -(13)$$

where L = the length of the screen

Q = the discharge

D = Depression at a distance x from the axis of the well, and

K = Coeff. of permeability of the soil.

4.02. The formula is based on the assumptions that :

(1) the water-table is of low slope.
(2) Velocity along water-table is proportional to tangent of its slope instead of its sine.
(3) Velocity is uniform along a vertical line, and
(4) Flow is horizontal at the water table and everywhere below.

Taking Q as a constant for the assumed conditions, the integration of equation No.13, within the limits x = r to x = R (where r is the radius of well and R the radius of influence), will yield the expression for discharge as :

$$Q = \frac{2\pi K D.(L + D/2)}{\log_e \frac{R}{r}} \qquad (14)$$

4.33. Theoretically, it is possible to obtain the value of the screen length for a certain desired yield with the help of the equation No.14, if other constants are known. Actually, however, it is difficult to estimate the average value of K which may vary widely for the surrounding soil. Another uncertain factor is the radius of influence R for which values varying from 500 ft. to 2000 ft. are often used, but which cannot be ascertained with any degree of certainty and is theoretically infinite.

4.34. For an approximate determination of the length of strainer to be provided, an empirical formula (based on statistical data), was suggested by K.L. Jain(19) -

$$L = \frac{Q}{10\ K.\pi.d} \qquad (15)$$

where L = length of strainer in feet.
Q = Discharge in gallons per hour at approx. 10 ft. depression.
K = characteristic discharge per square feet per foot of depression, and
d = diameter of tubewell pipe.

In this formula, K has to be calculated for different places, from actual observation and for the Indo-

Gangetic area the values have been found to range near about 8 to 12.

4.60. Thus, for a 33,600 g.p.h. discharge with a tubing of 6-in diameter (which for calculation purposes will be 7-in strainer diameter on account of strip and strainer gauze), the length of strainer necessary for the discharge will be :

$$L = \frac{Q}{10\ K.\pi.d.}$$

$$= \frac{33,600}{10 \times 10 \times \frac{22}{7} \times \frac{7}{12}} \quad \text{(Taking K = 10 per sq.ft.per ft. of depression).}$$

$$= 180 \text{ ft.}$$

DIAMETER OF WELL SCREEN.

4.61. The basic relationship Q = A.V. equation No. 17, indicates that with constant production the velocity of in-flow is inversely proportional to the diamete of the well screen. If the flow of the well is turbulent the friction loss at the time of entrance into the well varies approximately as V^2. Doubling the size of the well, therefore, reduces the entrance velocity to one-half and the friction loss to one quarter. The effect of reduction of entrance velocity is the reduction in sand-carrying capacity of the water.

4.62. From Equation No.14, it can be seen that fo two wells constructed in the same formation, same depth, same drawdown, and the same operative length of strainer the yield will vary inversely as $\log_e \frac{R}{r}$ and directly with K, (the permeability of the stratum). The values of

$$\left(\frac{1}{\log_e \frac{R}{r}}\right) \quad , \qquad (10)$$

however, change very little with changes in either R or r. Thus, the yield from the well changes very slowly with the increased diameter.

4.03. The question arises as to how much enlarging the diameter of a well screen will increase the production. A 12-in well will produce only 10 to 15 percent more water than a 6-in well, all other factors remaining same, while a 24-in well will produce from 20 to 35 percent more than a 12-in well. If a 12-in well yields 1000 gallons with 50 ft. of drawdown, a 24-in well will yield about 1200 to 1350 gallons only, with the same drawdown and drilled and completed under identical conditions. A relation worked out by E.W. Bennison(11), between the diameter and yield of wells with same depth, same screens and same formation, is shown in the figure.

4.04. In cases of centrifugal pumps, the velocity in suction-pipe is kept by most designers between 5 and 15 ft. per second. If the velocity is chosen in the neighbourhood of lower limit the size of tubewell is bigger and consequently more expensive, while if higher limits are chosen, the friction loss would be higher. Thus a velocity of 6 to 10 ft. per second would be most suitable to choose.

6.04. If Q is the discharge in cusecs and A the cross-sectional area of the tube in sq. ft.

Then the velocity $V = \frac{Q}{A}$ or $A = \frac{Q}{V}$ (17)

for 1.5 cusecs discharge, and 10 ft. per second, velocity.

$A = \frac{1.5}{10}$ = .15 sq. ft. = 21.6 sq. inches.

or d = 5.24 inch.

(say 6 inches)

6.05. When the water has to be collected from different strata and even if from the same strata, it has to be added up as the discharge goes on travelling from the bottom to the top of the tube. Thus, if the velocity is to be kept constant, the area of cross-section should go on decreasing from the top of the tube near the pump downwards to bottom. For practical purposes, it is obvious that stepping down the radius of screen and consequently of screens and blind pipe assembly will reduce the cost of the tubewell. But for such steps reducing sockets will have to be provided, and economy should be worked out for each case.

4.69. As the diameter of the strainer is increased it is by no means necessary to increase the size of the blind pipe also, so as to keep the two sizes exactly the same. The blind pipe is only meant to carry the water collected by the strainer to the top of the tube-well. Its size, therefore, is limited essentially to one suitable for the velocity of inlet water required for the type of pumping plant used. For instance in the case of a centrifugal pump, the most suitable velocity of water going to the suction of the pump is about 8 ft./sec. Therefore for a discharge of about 1½ cusecs the blind pipe of 6-inch diameter will be suitable.

4.70. In cases of deep borings the cost of blind pipe forms an important portion of the total cost of a tubewell. Therefore, the consideration of its size is all the more important, as the cost of such a pipe increases very rapidly with its diameter. The only use of keeping the blind pipe and the strainer of the same diameter will be that there will be no need of using any reducing sockets. The extra cost of these reducing sockets will be very much less than the extra cost of the bigger diameter blind pipes.

4.71. Choice of Parameters: Whatever may be the type of tubewell and chosen values of the screen length, screen diameter, and the rate of infiltration, it is necessary to choose a suitable value for depression also. The considerations involved in the choice are:

(1) The serious lowering of water level in the neighbouring tubewells or open wells.
(2) The cost of pumping.

4.72. The lowering of water table in the neighbourhood of a tubewell, when pumping, depends on a number of factors such as whether the aquifer tapped is confined or unconfined, then again whether the aquifer is fine, medium or coarse sand and gravel. With fine sand, the radius of circle of influence approximates the depression. In medium sand, this radius of circle of influence may be about twice the depression. In coarse sand and gravel this radius may be upto 10 times the value of depression.

4.73. The radius of influence is given by the formula:

$$R = \frac{S.(D^2 - d^2)}{2.3.D.\log_e \frac{R}{r}} \qquad (18)$$

where R = Radius of circle of influence
r = Radius of tubewell
D = Depth of water in the tubewell before pumping.
d = Depth of water in the tubewell while pumping.
S = Hydraulic slope.

4.74. The radius of influence seldom extends 1000 ft., and the lowering of water-table by less than one foot can be considered as inappreciable for all practical purposes.

4.78. The second consideration is the cost of pumping which depends upon the Horse power, given by the formula(31) :

$$H_w = \frac{Q \times 10 \times H_t}{33,000 \times 60} \qquad (19)$$

where H_w = water horse power.

Q = Discharge in gallons per hour.

H_t = Total head

= (Depression + depth of spring level from pump centre + static delivery head + Friction head + velocity head).

4.79. Taking all other factors as almost constant, it is evident that H_t will vary as depression and, therefore, the cost of pumping will increase as the depression is increased for a fixed discharge. This consideration puts a further limit on the choice of depression which should be kept as low as possible in order not to appreciably increase the cost of pumping which multiplies from hour to hour, day to day, and year to year.

4.81. In considering the design of a tubewell as a whole, it must be borne in mind that the discharge varies directly as the depression (equation No.14) and if the depression has to be reduced, a corresponding increase has to be made in either the length of screen, screen diameter, or the rate of infiltration, or in all, in order to obtain a fixed discharge. Increasing the screen length or diameter will mean higher initial cost and this must be balanced against saving in pumping cost.

CHAPTER. V

RIGHT MATERIALS FOR WELL SCREENS

8. RAW MATERIALS FOR WELL SCREENS.

8.01. Corrosive Behaviour of Groundwaters All groundwaters are more or less corrosive or encrusting, depending on the nature of the chemicals contained in it. The quantity of dissolved gases - particularly carbon dioxide - the relative solubility of the minerals, and the length of time the water is in contact with the various earth materials influence the quantities of minerals that are taken into solution. The carbon dioxide in water becomes carbonic acid, and since the solubility of most minerals is greater in carbonic acid than in pure water, the carbondioxide intensifies the solvent action of the water that wets the surface and sinks into pores or crevices of earth materials. The solvent power of the percolating water further increases as it picks up more carbon dioxide from the decomposition of organic matter or humus, in the soil.

8.02. The principal dissolved minerals in groundwater are in general, the bicarbonates, sulphates, and chlorides of calcium, magnesium, and sodium. Iron, Manganese, Silica, fluoride, nitrate and Hydrogen sulphide are also often present though in much smaller quantities.

8.09. The mineral contents of groundwater attack the metal of a well screen like they attack the rock materials with which they come into contact and thus corrode the well screen, or clog the screen openings by the formation of incrustations. The carbonates form a soft cementing deposit holding the other impurities and salts together, while the sulphates form hard scales. When selecting a well screen the possibility of corrosion and incrustation and their effect on the metal of the screen, should thus be seriously considered.

INCRUSTATION

8.11. Incrustation is the term used for the building up or depositing of minerals on and around the screen. Incrustation is not particularly harmful to the screen itself, rather it tends to protect the screen from corrosion. The harm comes from the fact that the screen and the voids in the surrounding formation are clogged by deposits of mineral salts brought in the water, being pumped.

8.12. *Cause of Incrustation.* The actual cause of depositing of the salts is the change in pressure that takes place at a well screen. As groundwater flows along through various formations, it carries in solution all of the mineral salts it will hold under certain pressure conditions. However, if the pressure is reduced at any point in this stream of water, CO_2 is released as a gas which, in turn, reduces the capacity of water to carry its full load of minerals in solution, (or the solubility of various salts in this water from which some CO_2 has been released, is reduced.), and consequently these salts are deposited.

8.13. Pumping reduces the pressure in the aquifer in the vicinity of the well by an amount equal to the drawdown, and in the case of tubewells, the maximum lowering of pressure occurs at the screen surface as is evident from the curve of depression and, therefore, the greatest tendency for the deposit is to form on and near this surface.

8.14. Forms of Incrustations. Generally the incrustation of screens, takes the form of a hard, brittle cement like deposit, while under different conditions, it may be soft and pasty like a sludge or even like a stiff jelly.

The incrustations may be :

(1) Due to the precipitation of materials carried upto the screen in solution such as carbonates of calcium and magnesium.

(2) Due to the deposition of soil materials upto the screen in suspension, such as clays, silts etc.
(3) Due to presence of iron bacteria in the water, (confined to waters containing organisms which grow by feeding on the iron in solution.)
(4) Due to slime - forming organisms other than iron bacteria.

In 90 percent of the cases, the incrustation is of the first type.

3.15. Effect of Silica: Silicon combined with oxygen in the form of the oxide SiO_2 is called silica, and quartz is almost pure silica in crystalline form. Water will dissolve only very minute quantities of quartz, nevertheless groundwaters sometimes, do contain as much as 100 ppm Silica(33). Silica does not contribute to hardness of water, however, it is an important part of the incrustants or scale formed by many waters. As deposited, the scale is commonly calcium magnesium silicate.

3.16. Effect of Iron: Iron concentrations greater than 0.3 p.p.m. are usually troublesome. Water may pick up iron from contact with well casing, pump parts, and piping. The more corrosive the water, the more metal it will dissolve from the iron surfaces with which it comes in contact. Upon contact with air the dissolved iron, which is in the ferrous state, changes to the ferric state and comes out of solution. The chemical compounds formed by this oxidation are iron hydroxide, and iron oxide.

5.17. Iron bearing waters also favour the growth of iron bacteria such as crenothrix(63). The bacteria are all surrounded by a filamentous sheath, and the filaments grow attached to the well pipe, and in the voids of the water-bearing material. The sheath developed, is a jelly like slime that can seriously clog the pores of the water bearing formation and the openings of the well screen.

CORROSION

5.18. Corrosion means the loss or wearing away of the screen material. The process of corrosion is a surface phenomenon. Its causes are electro-chemical in nature, chemical because corrosion is due to reactions of the metal with different elements or compounds in the water, and electrical, because these reactions require a concurrent interchange of electrical charges. There are three types(67) of corrosion that usually occur in conditions under which a tubewell screen is placed :

(1) Direct Chemical
(2) Dezincification, and
(3) Electrolytic.

5.22. Direct Chemical Corrosion. It is recognized by a uniform even destruction of the surface of the metal leaving the body of the metal in its original condition. When this type of corrosion attacks a well screen, it is found that the slots are enlarged from two to ten times the size of the original slot. In this type there is no separation into anodic and cathodic parts, and the strength of the screen is reduced only to the extent the thickness of the metal is reduced by the corrosive action.

5.23. Dezincification. Dezincification or selective corrosion results from the electro-chemical difference in potential between the metals in the alloy, and is a form of the electrolytic corrosion. The most favourable conditions fo this type of corrosion are where there is a good conducting solution such as a brine, or slightly acid condition with the presence of oxygen and a two metal alloy.

5.24. Electrolytic Corrosion. This type of corrosion is the familiar action resulting when a common two-metal galvanic cell is set up. This is caused due to the difference between the individual tendencies of the two metals to be acted on by corrosive solutions. An electric current is generated and this is the driving force behind the corrosion reaction, with the corroded metal part in the cell as the anode, and the protected one as cathode.

3.28. If metals are arranged in the order of their tendency to corrode galvanically, the following approximate arrangement(07) will result :

> (Corroded End, Anodic), Magnesium, Magnesium alloys, Zinc, Aluminium, Cadmium, Steel or Iron, Chromium-Iron, Chromium-Nickel, Lead, Tin, Nickel, Brasses, Copper, Bronzes, Copper-Nickel alloys, Monel, Silver, Gold, Platinum (Protected End, Cathodic).

when two dissimilar metals some distance apart in the above series, are joined and immersed in an electrolyte the metal higher on the list will be corroded. Metals close together on the list have little tendency to produce galvanic corrosion on each other.

3.29. Loss of Materials. The loss of material due to corrosion can be calculated in gms/sq.meter/hour. According to the usual definition the material is regarded as entirely corrosion-proof or "Stable"(05) if it shows a loss of weight of less than 0.1 grammes/sq. meter per hour. The material is defined to be "Unstable" where a loss of weight of more than 10 gr/sq.meter/hour takes place. On the basis of these losses of weight the depth of the penetration of the corrosion per year can be calculated in so far as there is a uniform decomposition over the whole surface.

5.31. *Factors Affecting the Rate of Corrosion:* The rate of corrosion of well screens varies greatly due to the various factors involved, that may be grouped under :

(a) Composition of Screen Materials,
(b) Temperature and rate of flow, and
(c) The water quality.

5.32. Impurities in the metal, and segregation of the constituents of the well screen by improper manufacturing methods, lead to higher corrosion rates. In each case galvanic currents are generated between the different metals and the more electro-positive one of any couple is corroded rapidly. The rate of corrosion further increases with higher temperature, and the increase in the velocity of tubewell water, being pumped.

5.33. The effect of water quality on the rate of corrosion is mainly due to ionisation of groundwater in which the screen is placed. The factors(67) contributing the effect of water quality on the rate of corrosion, may be listed as :

(1) A low hydrogen-ion concentration or pH value, coupled with low alkalinity, low hardness and high content of free carbon dioxide.

(2) A water with a high content of dissolved oxygen which by combination with liberated hydrogen prevents the formation of a protective film.
(3) The presence of organic acids.
(4) The presence of hydrogen sulphide, sulphur dioxide or similar gases, and
(5) The presence of iron sulphate and other less common causes of corrosion.

5.41. Influence of pH. The pH value of most groundwaters is controlled by the amount of dissolved carbon dioxide gas and the dissolved carbonates and bicarbonates in the mineral salts. A pH value of 7 indicates a neutral solution, that is, neither alkaline nor acidic. A pH less than 7 indicates an acid condition, whereas, a pH greater than 7 corresponds to an alkaline solution. Free mineral acidity is present only when the pH is below 4.3(63). The more acidic a particular water is, the greater corrosion it is likely to cause.

5.42. In an alkaline solution, there is a general trend of increased corrosion rates with increased pH, in the pH range (7 to 8.6)(63), and detailed laboratory investigations by Larson and Skold, has indicated that the lowest average corrosion rate occurs around pH = 7.

5.51. Specific Conductance. Specific Conductance or the specific electric conductance is the ability of a substance to conduct an electrical current. Water with relatively high specific conductance can cause corrosion of iron and steel even though other properties may not indicate a corrosion problem. Since specific conductance reflects the activity of the electrically charged ions in the water, it follows that the higher the conductivity the greater is the opportunity for electro chemical action.

8.82. Chemically pure water has a very low electrical conductance, however, in solution as dilute as most groundwaters, the specific conductance varies directly with the amount of dissolved minerals in the water.

8.83. High values of conductance speed up the galvanic corrosion when a two-metal well screen is used. High conductance also promotes more rapid corrosion of steel alone. A slotted steel pipe in a well in Montana(60) (U.S.A.), was found to have been totally corroded within only two years time, due to the high specific conductance of the water alone, the other characteristics being not corrosive.

8.84. *Hydrogen Sulphide.* Hydrogen Sulphide(H_2S) is another gas sometimes found in natural groundwaters, that makes the water corrosive. Hydrogen sulphide attacks most copper base alloys if an appreciable proportion of the gas is contained in the water. The reaction produces copper sulphide which is insoluble and may be deposited in the openings of the well screen. Thus, a situation may arise in this case, where the metal of the screen is eaten away by the corrosive element and the product of corrosion is deposited in the screen openings causing incrustation of the screen at the same time.

5.69. *Dissolved Oxygen.* Dissolved oxygen(O_2) speeds up the corrosive attack of water upon iron, steel, galvanized iron and brass. If the temperature is increased, the rate of corrosion tends to increase but the amount of oxygen in solution decreases with higher temperature and this may counteract the other effect, unless heated water is under pressure. Water with dissolved oxygen corrodes metals more rapidly when the pH is low. High pH values tend to retard the attack. However, a water with relatively high electrical conductance, will be aggressive even though the pH may be 8.0 or more.

5.71. *Corrosion Resistant Materials.* The structural considerations of well screens demand the use of materials of only good quality, ensuring greatest corrosion resistance, while the economic considerations require the employment of these metals which are relatively cheap though corrosive.

5.72. The considerations of the heavy costs associated with the failure or breakdown of the corroded screens on the other hand, indicate that the well screens made of corrosion resistant material, even though they may be higher priced, are always cheaper in the long run. The possible choice ranges from the most corrosion-resistant stainless steels and bronzes down to ordinary low carbon-steel.

5.73. The Agricultural and Zoj strainers and the U.S. Slotted pipes, generally used for tubewells in this country have been found to give poor efficiencies, since their materials are likely to introduce and accelerate corrosion with consequent well failures.

5.74. The metals and alloys which have been found and developed to be most effective against the agencies attacking well screens under all conditions of soil, groundwater, use, and pressure, graded in order of their ability to resist attack, may be listed as :

(1) Monel Metal (Approx. 70% Nickel and 30% copper).
(2) Cupro-Nickel Metal (70% Copper, 30 Nickel, and 1% arsenic).
(3) Everdur Metal (96% Copper, 3% Silicon, and 1% manganese).

(4) Stainless Steel (74% Low Carbon Steel with not more than .08% carbon, 18% Chromium and 8% Nickel)
(5) Silicon Red Brass (83% Copper, 1% Silicon, and 16% Zinc).
(6) Common Yellow Brass (67% Copper, 33% Zinc).
(7) Plastic Coated Steel (Polyethylene).
(8) Hard Rubber Coated Steel.
(9) Low Carbon Steel.
(10) Bituminized Steel, hot-spelter galvanized steel, Chlorinated rubber coat and hard Rubber coated Steel (Rust Resisting only).

8.75. On account of the greater advantages and the bearable costs, Polyethylene Steel, Stainless Steel, and Everdur Metal have lately become more popular in the field of well screens particularly in the U.S.A. and Germany.

8.76. <u>Polyethylene Steel.</u> The most recent development for anti-corrosive well screens, is the introduction of a new high quality plastic material, polyethylene, the properties of which make it a simple ideal protective agent for screen against corrosion. Polyethylene is a paraffin of a tough leather, like character, and has excellent resistance against chemical influences. The new plastic material has gained outstanding importance and the author found in Germany these screens being used more and more on the recent wells, on account of their cheapness in comparison to copper, bronze, or stainless steels.

5.77. Stainless Steels. The stainless steels actually require exposure to some Oxygen in order to attain their highest corrosion resistance. Oxygen combines with the surface of the metal to form an invisible protective film. As long as this film is intact, the metal is in the passive state, and its corrosion resistance is extremely high. If the film is, however, destroyed and no Oxygen is present, the surface of the metal changes to the active state, and it becomes as vulnerable to corrosion as ordinary steel or wrought iron.

5.78. Everdur Metals. The corrosion resistance of Everdur(44) metal exceeds that of any brass alloy because it contains no Zinc. Its manganese content gives it the tensile strength of steel and the silicon content makes the alloy weldable. Oxidizing conditions cause more rapid corrosion of most copper alloys and hence cupro-nickel and Everdur metal are not suitable to such conditions.

5.79. Everdur metal is normally more corrosion resistant to sea water, however, where conditions are such that a considerable amount of dissolved oxygen is contained in the sea water that may be pumped through wells, stainless steel should be the choice for screens. Stainless steel is more difficult to machine than Everdur, so that making threaded connections is more costly. However, the screen sections can easily be welded, and the welded joints have the advantage of being much stronger than threaded joints.

8.01. Cathodic Protection for Well Screens. The corrosion of well screens can be avoided or mitigated by the use of a new process known as Cathodic protection. It renders protection to well screens of normal and hot spring [illegible] wide-spread application during the last five years, particularly in the U.S.A. and Germany. The cathodic protection counteracts the corroding effect of the current flowing from the metal surface of the local anodes.

8.02. In the actual process cast or extruded anodes made of special magnesium alloys are used. A good electrical connection is established between the magnesium anode and the metal of the well screen to be protected. In this way a galvanic cell is formed in which the metal to be protected acts as cathode. The protective current flowing from the galvanic anode through the electrolyte to the cathode has a direction reverse to the local corrosion currents emerging from the local anodes to the (surface) to be protected, and is able to fully compensate the local currents, provided that the protective device is adequately adjusted. Thus, any further corrosion attack is eliminated.

5.01. [illegible], The choice of right materials for well screens, thus necessitates a more exact study of the dissolved minerals and gases in the natural ground-waters, and the effect of such waters upon the well screens. It is desirable to test the well water at least for :

(a) Its pH value, thus establishing its acidity or alkalinity.
(b) Presence of Carbonates.
(c) Presence of Sulphates.
(d) Presence of Suspended Impurities.
(e) Presence of dissolved Oxygen, and
(f) The specific electric conductance.

5.02. Knowing the quality of water and the soil conditions a suitable screen material to withstand the corrosive actions, can be selected from the various listed corrosion resistant materials keeping the economical factor in view. For example, where it is anticipated that dissolved Oxygen will be present in more than ordinary amounts in the water being pumped, stainless steel screens will be the best choice.

5.03. If the pH value is lower than 6 the water is likely to be very corrosive. In bad cases it will be advisable to reduce the depression and thus the rate of pumping, and it may even be necessary to plan two tubewells instead of one.

-X-X-X-

SECTION. (2)

(GRAVEL-PACKS)

CHAPTER. VI

BASIC REQUIREMENTS AND REVIEW OF LITERATURE FOR DESIGN OF GRAVEL - PACKS

6. BASIC REQUIREMENTS AND REVIEW OF LITERATURE

6.01. Basic Considerations. From the basic considerations, if any unit volume is packed with spheres of equal diameters, the ratio of voids to non-voids will be maximum for the equal size of spheres regardless of their diameter and will always be reduced whenever some spheres with larger, or smaller diameters than the rest are introduced. Thus the voids or space available for flow of water will be maximum in a uniform sized formation and comparatively less when there is a heterogeneous mixture of grain sizes in any formation.

6.02. In a hypothetical case of two formations, one composed of fine spherical particles and the other of bigger spherical particles, of uniform size, though the total voids may be the same in both the cases, yet the surface forming the voids in the case of fine grains will be much larger than that in the case of coarse grains.

6.03. Greater surface causes greater friction to flow of water, and since the fine capillaries have higher surface tension a greater force would be required to make the same amount of water flow through a finer formation than a coarser one. Thus for higher yield with lower depression, it is necessary to have as coarse and as uniform a formation as possible, particularly in the immediate neighbourhood of screen forming the tubewell.

6.04. Any change brought about in the size, shape, number or arrangement of sand grains in the immediate neighbourhood of a tubewell, around the tube, substantially affects the value of the rate of infiltration. In practice, this scientific fact, has led to development of gravel packed (or gravel shrouded) tubewells where the tube forming the tubewell is shrouded by gravel of properly selected sizes to give improved rate of infiltration.

6.05. The rate of infiltration though a constant, yet can be artificially made to behave as a variable by the use of a properly selected gravel envelope. Thus where the formation of strata is such that choice of variables length and radius of screen is not sufficient to be able to design a tubewell to give the required yield, the possibility of improving the rate of infiltration by use of properly selected gravel pack gives yet another weapon for the design of tubewells.

6.11. Function of Gravel-pack. The basic function of the artificial gravel envelope is to provide a highly permeable mass to fill part of the space in the drilled well so that a greater yield is obtained and a smaller diameter well screen can be used than would otherwise be required. While artificial gravel-packing does permit the use of somewhat larger slot openings in the well screen than would be needed without the gravel fill, it is however, not the primary reason for employing the gravel envelope design, except in formations of very fine sand.

6.12. Thus, the purpose of gravel packing is to get more yield or in other words to enable a water-bearing strata to yield sand free water to its maximum capacity if required with the least depression. The advantages of proper gravel packing may be enumerated as :

(1) Increased yield or specific capacity for the same amount of pumping due to reduced depression.
(2) Increased yield on account of larger effective diameter of the well and decreased screen velocity.
(3) Possibility of use of larger size of slots in the slotted tube.
(4) Water more free from sand particularly in fine sand formations.

6.13. Formation Requiring Gravel-Pack. All water-bearing formations do not require gravel packing as their natural grading may be such that they can be developed to their full-water yielding capacity without any gravel packing. The gravel-packing is, however, required :

(1) In a well graded aquifer with a large percentage of fines, in order to avoid sand pumping, and
(2) In case of fine grained aquifers to permit use of large slot sizes and a greater percentage of open area of the well screens.

6.31. Design Principles. Several studies have been made of filters for hydraulic structures, in the United States and other countries, while only a few of these were intended to apply to irrigation wells. The design of filters is based on four basic principles and the material selected for the gravel pack must satisfy them fully.

(1) It must be fine enough to prevent the passage through its pores of particles from the formation material.
(2) It must be coarse enough so that the head dissipated by flow of water through it, and therefore the seepage forces developed within it, will be relatively small.
(3) It should not have its uniformity coeff. greater than 3 or else the smaller size of gravel is likely to get separated from the larger size in a uniform mixture during its passage through the water to the bottom of the well while being poured in.
(4) The layer of the gravel pack must be sufficiently thick to provide a good distribution of all particle sizes throughout the gravel envelope.

6.32. In addition to the four basic requirements, it is most desirable that :

(a) The curve of the enveloping gravel when plotted should preferably approximate to the shape of the cumulative curve obtained by sieve analysis for the strata formation, and
(b) The gravel used must be clean and of good quality carefully selected as pea or round shape.

6.33. On theoretical considerations, a basic relationship for the filter design can be obtained by considering three large spheres of equal radius R, touching each other and a smaller sphere of fixed size of radius r, touching all the three(71). In such a case, (referring to fig.).

$$R = 6.45\ r \qquad (20)$$

6.34. Applying this mathematical relation to the practical problem of selecting a suitable gravel packing material, it will be observed that the gravel used should be less than 6.45 times the diameter of the sand grains desired to be blocked by gravel pack. In practice, however, it is neither possible for the gravel pack material to be all graded as equal size spheres, nor is the water-bearing formation composed of equal sized sand grains. Thus, the problem becomes more complicated.

<u>Review of Literature.</u>

6.41. <u>Terzaghi's Criterion</u>: The criterion for filter design (though initially for dams) as suggested by Terzaghi(83), and which, after investigations of its validity, has been recommended by the U.S. Waterways Experiment Station may be written as :

$$\frac{D_{15}\text{ (of filter)}}{D_{85}\text{ (of foundation)}} < (4 \text{ to } 5) < \frac{D_{15}\text{ (of filter)}}{D_{15}\text{ (of foundation)}} \qquad (21)$$

The first two terms state the first requirement; to prevent the formation material from passing through the pores of the filter, the 15 percent size of the filter material must not exceed 4 to 5 times 85 percent size of the formation material. The second and third terms cover the second requirement, to keep seepage forces within the filter to permissibly small magnitude, the ratio of 15 percent sizes of filter and formation materials must exceed 4 to 5.

6.42. U.S. Corps of Engineers Criterion. The U.S. Corps(88) of Engineers on tests of drainage well filters concluded :

(1) Terzaghi's filter criteria are sound.
(2) The grain size curve for filter and formation materials should be approximately parallel.
(3) Filter materials should be packed densely.

6.43. U.S. Bureau Criterion. The U.S. Bureau(93) Criterion based on the basis of uniformity coefficient

of the gravel pack and the aquifer suggests that:
If uniformity coefficient (D_{60}/D_{10}) of the aquifer is less than 2, but effective size (D_{10}) is greater than 0.3 mm, no gravel pack should be provided. If the uniformity coefficient is, however, less than 2 and the effective size less than 0.3 mm, a uniformly graded gravel pack is indicated. To obtain this multiply 50 percent size of the aquifer material by 5 and 10, plot the products on 50% abscissa, draw lines through each of these two points approximately parallel to average slope of the aquifer gradation curve. These lines are the limits of the most satisfactory pack. If the gradation curve falls outside these lines to the right, the material would not stabilise the basic aquifer material and should not be used. If it falls outside and to the left it would stabilise the aquifer material, but the well is likely to be less efficient.

C.44. If the Uniformity Coefficient is greater than 2, then:

$$(a)\ 12 < \frac{D_{15} \text{ of (filter)}}{D_{15} \text{ of (base)}} < 40 \qquad (23)$$

$$(b)\ 12 < \frac{D_{50} \text{ of (filter)}}{D_{50} \text{ of (base)}} < 58$$

In this case a graded pack of larger effective size is indicated. To obtain this, multiply 50 percent size of the aquifer material by 12 and 58, plot the products on 50 percent abscissa multiply 15 percent size by 12 and 40 and plot the products on 15% abscissa. Connect these points with straight lines. The gradation curve of the pack material should fall within these lines and be approximately parallel to the aquifer abscissas.

6.45. As Per Colorado State University (Fort Collins) recommendations(70), for a uniform aquifer, a uniform gravel pack with pack-aquifer ratio of about 9.5, or a non-uniform gravel pack with a pack-aquifer ratio of 13.0, may be provided. If the aquifer is non-uniform, uniform or non-uniform gravel packs with greater pack aquifer ratios than allowed for uniform aquifers, may be used.

6.46. [illegible](72) and [illegible], after running a series of tests on uniform aquifers and gravel packs at Colorado State University, on a six-inch plastic tube model, suggested that the head loss is minimum at the highest stable pack-aquifer ratio, and that the amount of aquifer material moved varies directly with velocity of water through the aquifer pores, the hydraulic gradient in the aquifer, and the pack-aquifer ratio.

6.47. According to Mr. E.W. Bennison(73), if effective size (D_{10}) is greater than .01 inch, and uniformity coefficient lies between 5 and 10, the well does not require gravel packing. Gravel packing is, however definitely needed if the uniformity coefficient is less than 2.

6.48. E.W. Bennison also suggested that the minimum thickness for proper gravel pack is 3 in, while the maximum is 12 inch. Very thick gravel packs should be avoided as they are likely to be clogged with fine sand. The velocity of water through a very thick gravel pack is likely to fall so low as not to be able to carry fine sand particles through it while developing them, causing them to drop out in the interspaces of the gravel packing.

6.49. H.L. White(78), made recommendations for the gravel to be used, and suggested that :

(a) The size of gravels in the gravel envelope should be determined from the size of sand grains of the formation, to be screened out.

(b) Shape-spherical is ideal.
(c) Character Hard granite like material.
(d) Condition-Clean washed, and of uniform size.

CONTRIBUTION TO YIELD FROM VERTICAL WELL IN GRAVEL ENVELOPE.

6.51. Popular opinions of what artificial gravel-packing can or cannot do for well construction are often wrong. One example of this is the idea that large quantities of water can flow through the gravel envelope vertically between one water-bearing stratum and another which lies at a greater depth. The fact is, however, that relatively very small quantities of water can be passed vertically through the gravel envelope down to the well screen from a separate aquifer at some elevation above the well screen, even under the most favourable conditions.

6.52. Taking the example of a 6-inch well casing with 16-inch drilled hole, the cross-section area of the space filled with highly -permeable granular material designed to control the sand of the water-bearing formation $= \pi\left(\frac{16^2}{4} - \frac{6^2}{4}\right)$ (23)

$$= \pi(64 - 9)$$

$$= 55\pi \text{ sq. inch.}$$

$$= 1.2 \text{ sq. ft.}$$

6.53. Referring to figure, any water that enters the well from the upper stratum of sand must flow downward through the gravel envelope for a distance of 50 feet. The head causing this vertical flow is equal to the drawdown in the well which is 25 ft. The static level is assumed to be the same in both strata. The hydraulic gradient under which the flow takes place

$= \frac{25}{50} = 0.5.$

6.54. Assuming the permeability of the lower water-bearing formation to be 1,000 gallons, per day per sq. ft; and that of the gravel used to be 10,000 gallons per day per sq. ft., and using the formula based on Darcy's law, we have :

Q = K. i. A. (26)

Where Q = the flow rate in gal. per day.
i = the hydraulic gradient.
A = the area in sq.ft. through which the flow takes place.
K = the permeability of the gravel in gal. per day per sq.ft., under a hydraulic gradient of unity.

Thus Q = 10,000 x 0.5 x 1.2
= 6,000 gal. per day.
= 4.25 gal. per minute.

This calculation assumes that the gravel column is perfectly clean and open, which is not likely to be the case in practice.

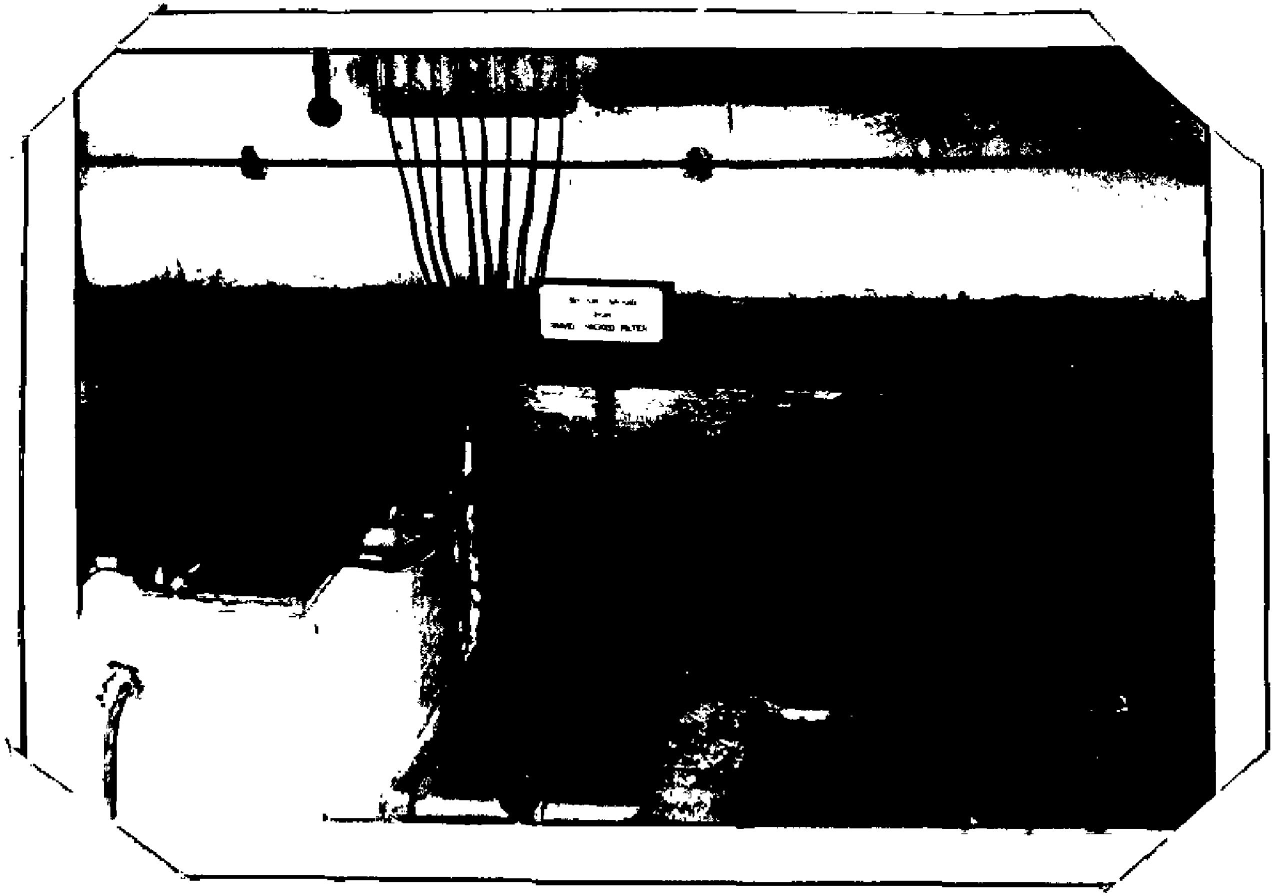
6.55. If the upper sand should have a permeability of 1200 g.p.d. per sq. ft. and a 10-ft. section of the well screen were installed between the depths of 79 ft. and 95 ft., the yield from the upper sand would be about 100 g.p.m.

6.56. The contribution to yield from vertical flow in gravel envelope under the conditions of this example is thus, only about 4% of the potential yield of the stratum. This analysis clearly shows that the plan for a tubewell should contemplate no important contribution to yield from assumed vertical flow through the gravel envelope. It further demonstrates the greater advantage of properly placing sections of the well screens, to correspond with the depths of strata that are capable of yielding substantial quantities of water to the well.

* * *

CHAPTER. VII

EXPERIMENTAL APPARATUS & PROCEDURE
FOR
DESIGN OF GRAVEL PACKS



GENERAL LAYOUT.

FIG. NO 7.02.

7. EXPERIMENTAL APPARATUS & PROCEDURE.

7.01. Experimental Apparatus. The current tests on gravel packs were conducted by the author to obtain design criteria for the selection of suitable gravel packs in combination of the uniform as well as non-uniform aquifers. A transparent radial model was used so that the effect of increase of velocity towards the centre of the well and the movement of the aquifer could be observed.

7.02. The model consisted essentially of the following :

(1) The wedge-shaped perspex Sect~~ion~~or-Box.
(2) A controlled flow arrangement.
(3) The clamping device.
(4) The piezometer arrangement.
(5) A constant head Tank and, The V-notch chamber.

7.03. The wedge-shaped sector-box consisted of a 30° wedge of ½-in thick perspex, eight inches high and with a 30-inch radius. The top and bottom each, consisted of trapezoidal plates with 4.25-inch and 22-inch as parallel sides, placed, 30 inches apart. The bottom was fixed to the vertical walls with the help of 24 nos., 1-inch long brass screws, and the top provided with two air vents was kept removable for the replacement of the aquifers and the gravel packs. A 3/8"x 1/8" groove, 2" away from the edges, both in the bottom and the top plates provided for a better securing of the vertical walls. A rubber gasket was used in the groove for a water-tight compartment.

7.04. The tip of the wedge represented the centre of the tubewell with a 6-inch casing and 9-inch thickness of gravel pack. A section of the perforated well casing with 2" x 3/32" staggered slots (cut in vertical direction), was located 3 inches from the tip of the edge. A fine wire copper mesh two feet three inches from the tip contained the aquifer material. A nine-inch thickness of gravel pack and a 19-inch thickness of aquifer were placed between the two screens.

7.11. Controlled Flow Arrangements. The controlled flow arrangement consisted of the separate inlet and outlet, and a reverse flow line, each of 1-inch diameter G.I.Pipe. The flow was controlled by six steam-wheel valves. When valves 1 and 3 were open, flow occured from inlet to outlet. Closing the valves 1 and 3 and simultaneously opening the valves 2, 5 and 6, caused a reversal of flow in the model. The valves required about one fourth of a minute to close so the flow reversals were not instantaneous.

PIEZOMETER

ARRANGEMENT.

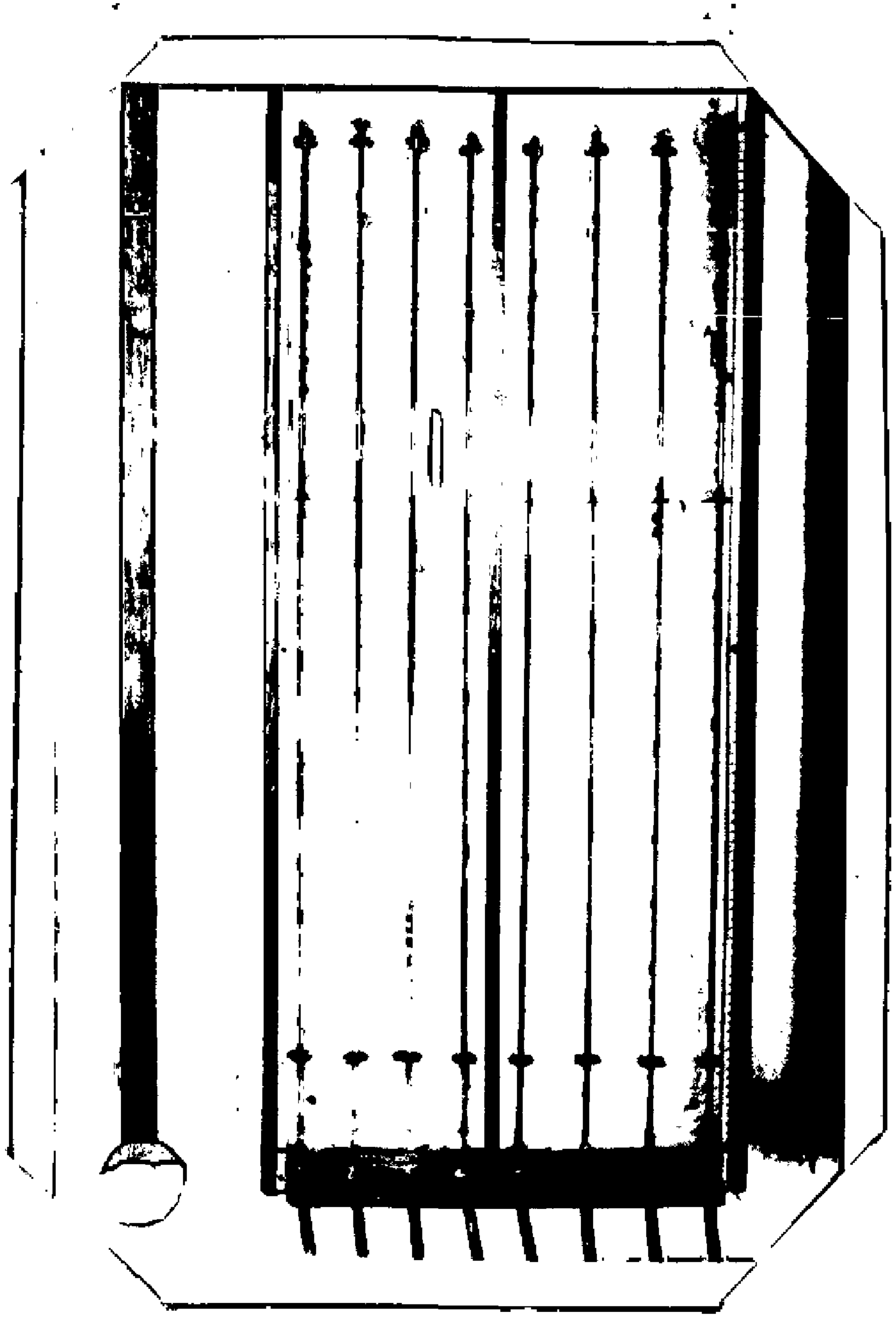


FIG. 7.31

was taken from a constant head tank located about 14 feet above the model. The large volume of the tank aided in keeping a uniform water temperature during the tests. The discharges were measured with a calibrated 90° V-notch weir, set in the end of a V-notch chamber which was 6 ft. long, 2 ft. wide and 2 ft. 6 in. deep. For stilling the flow in the V-notch chamber a 2" thick concrete baffle wall was installed 5 ft. upstream from the weir. The depth of flow over the weir was measured with a hook gauge located 3 ft. upstream from the weir. The hook-gauge measured to one thousandth of an inch.

PROCEDURE AND METHOD OF TESTING.

7.31. Controlled Compaction. In the study of the flow of sand into wells and the accompanying changes in the head losses, it is recognized that the degree of compaction of the gravel envelope and the water bearing formation might have considerable effect on the results obtained. For this reason a standard procedure was adopted for conducting the tests. The first time each material was used, it was packed into the model as compactly as possible by rodding the material. The dry weight of material so compacted was recorded. For later tests with the same material, the same weight was used. Since the material was placed in the same volume, uniform compaction resulted.

7.52. The gravel packs, to be tested, were placed between the well screen and a sheet metal partition, and the aquifers between the partition and the aquifer screen. When both materials were in place and compacted the interface partition was removed. The aquifers and gravel packs were placed in the model in a damp condition. This technique held segregation of different sized particles to a minimum.

7.61. Air Removal. When getting ready to make a test, the top of the model was clamped with the clamping device, and the inlet end was raised about six inches. When water was introduced at the outlet end, air was forced from the granular materials and drained from the model. While the model was being filled, both the air vents along the top of the model were kept open. After all the air visible in the model had escaped the air vents were closed and the model was lowered to its horizontal position.

7.62. The piezometers along the side of the model were then opened one at a time and allowed to discharge until all the entrapped air had escaped. As soon as the flow became uniform, the piezometer was connected to the proper glass tube on the manometer board.

7.69. When all the piezometer connections had been made, the levels in the manometers were checked to see whether there was air entrapped in any of the rubber tubes. This could be easily determined because the glass tubes on the manometer board were arranged in the same order as the piezometers and consequently any radical change in the difference between levels in adjacent tubes was immediately apparent. Disconnecting the rubber tube at the piezometer and allowing the water to flow out of the manometer took care of this trouble.

7.71. Recording of Readings. When all the manometers were working properly, the flow through the model was adjusted by regulating the valves on the inlet and outlet pipes until the correct head was indicated by the hook-gauge over the V-notch weir for the desired discharge. This adjustment was made as quickly as possible because variations in the rate of flow would affect the amount of sand movement. It was attempted to hold discharge constant during the remainder of the test.

7.72. Readings of the discharge and piezometric heads in the model were taken at 10-minute intervals for the first 30 minutes of the test. Then, after the head readings had stabilized the flow was reversed and re-reversed at five-minute intervals. When a flow cycle did not change head readings or when failure of the filter due to aquifer movement was evident the test was stopped. For most stable combinations of materials it was seen that four to five surges were sufficient to stabilize head loss in the model.

7.73. The preliminary tests showed that the heads registered by the piezometers did not hold constant. As the sand moved into the gravel envelope the total head loss at first increased and then after most of the sand movement had stopped, the head loss gradually decreased. Because the initial reading of the head loss was affected by the time required to adjust the flow, these readings were discontinued and the readings at the end of the tests only were taken.

7.74. After the manometer readings had been recorded, the inlet valve was closed, the rubber tubes at the piezometers were disconnected and the air vents on the top of the model were opened. This permitted the water to drain slowly trhough the outlet.

7.75. When the water had drained down to the level of the outlet connection, the inlet and the outlet were disconnected and the whole sector-box was weighed in order to find out the amount of sand moved. The interface partition was then re-inserted and samples of gravel pack were taken near the interface and at the centre of the filter. These samples along with the remainder of the gravel pack were dried and sieved to determine the amount and location of aquifer penetration.

7.76. A complete record of each test was kept. The record consisted of the type of size of perforations of the well-screen, the size of sand in the aquifer, the size of gravel in the envelope, the manometer readings, the gauge height and the weight of the sand moved.

-H-X-X-H-

CHAPTER. VIII

LABORATORY TESTING PROGRAMME

C. LABORATORY TESTING PROGRAMME.

C.01. The laboratory programme for testing was divided into the following parts :

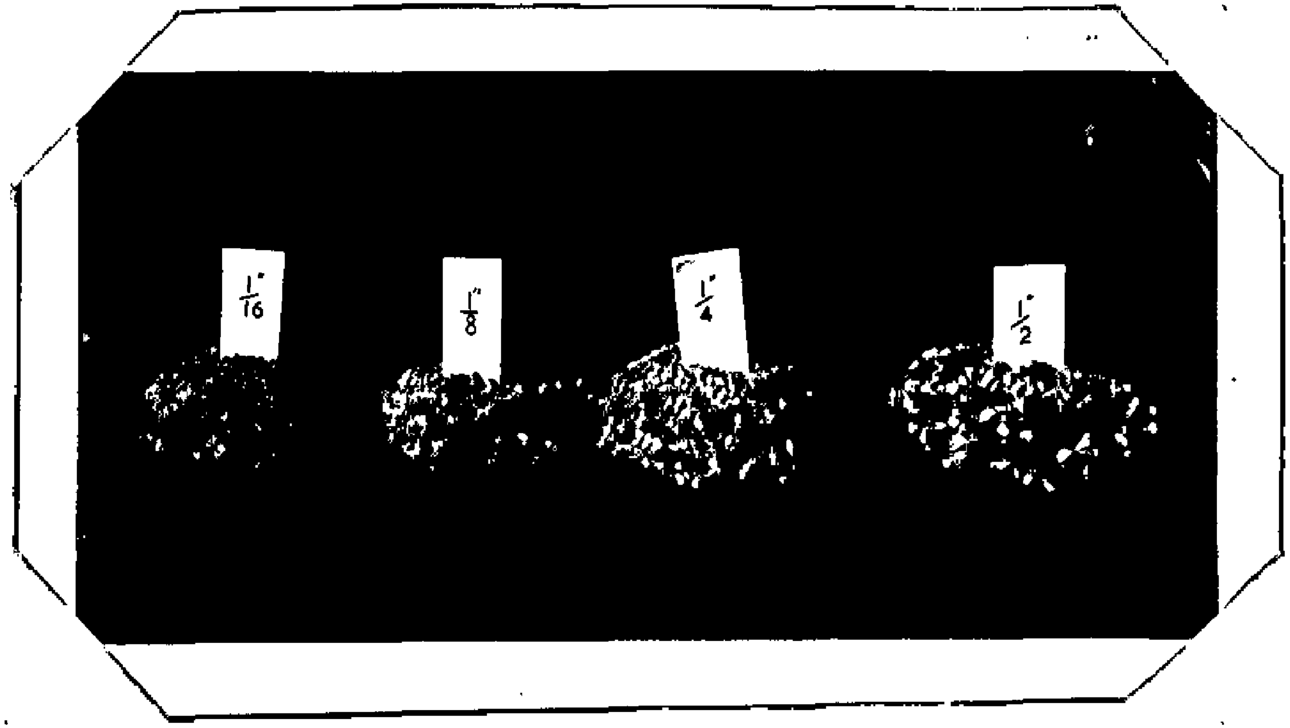
(a) Determination of suitable criteria for the design of a uniform gravel pack for uniform aquifers.
(b) Determination of suitable criteria for the design of a uniform gravel pack for non-uniform aquifers.

C.02. Uniform and Non-uniform Materials. A uniform grainsize material is defined in this paper as a material having an approximate straight-line gradation curve and a narrow range of major particle sizes with an allowable variation in approximate range of uniformity coefficients from 1.5 to 2.0. A graded or non-uniform material, on the other hand is defined as a material having a comparatively broad range of particle sizes. Graded material may have concave, convex, S-shaped, or straight line gradation curves and may be defined as "poorly" and "well" graded material, depending on their gradation curve shape.

C.11. Stability Control Factors. The physical properties of uniform grain-size material are characterized by degree of fineness, as represented by the mean grain-size, which is approximately represented by the 50 percent grain-size. For most formation material of natural gradation, the mean grain-sizes fall between 40 and 60 percent. Therefore, the relationship between the 50 percent size of gravel material and 50 size of the formation material was chosen as a control factor for stability of uniform graded filters.

6.12. Differentiation between stability and failure of a filter-aquifer combination was made somewhat arbitrarily. It was observed that, when continuous sand movement was evident during the course of the test, sieving afterwards showed more than 150 gms. of aquifer having moved into the gravel pack. Similarly when more than 150 gms. of aquifers moved, continuous changes in piezometer head readings in the model were usually observed. Also surging did not cause a reduction in head loss at the pack-aquifer interface. Therefore, in general, tests in which more than 150 gms of aquifer material moved into the gravel pack were considered to be unstable.

6.21. <u>Test Sands and Gravels.</u> Sand and Gravel for the test filters were prepared for testing by carefully sieving into fractions retained on each sieve in a standard series (1½" to No.200). These materials were



TEST GRAVELS.

FIG. NO. 8-22.

washed, oven dried, and stored in covered buckets to prevent gathering of dust. From these materials the uniform grain size gravels and uniform and non-uniform formation materials of different gradations were artificially prepared and the sieve analysis of the aquifer and gravel materials were made. River-bed gravel was used because this gravel had been subjected to erosion which tends to round off the sharp corners leaving the gravel more or less spherical in shape.

8.22. The gravel used in each of the gravel packs contained particles that were approximately of the same size. The particle sizes used in the gravel envelopes for test were ½, ¼, 1/8 and 1/16 inches. Even after careful screening the particles were not all of the exact sizes indicated.

8.23. The same well screen was used in all the experimental tests. The screen consisted of 30° sector of 6-inch diameter C.I. pipe, with 2"x3/32" size staggered slots (cut in vertical direction). The coefficient of the well screen was 19.1 %.

8.31. <u>Grouping of Tests.</u> The experimental tests of gravel packs with uniform grain-sized formation materials consisted of four group series A, B, C and D with a different type of formation material for each group.

8.32. Each group was divided into two sections for two different velocities in the aquifer material, and each section was sub-divided into different parts of different size of gravel material for packs. The results of the test data for different combinations of uniform gravel packs with uniform aquifers are given in Table Nos. 8.33, 8.34, 8.35 and 8.36.

8.41. The experimental tests of gravel packs with non-uniform grain-sized formation materials consisted of another four group series A_1, B_1, C_1 and D_1, having an identical formation material for each group. The results of the test data for different combinations of non-uniform aquifers and gravel packs are given in Table Nos. 8.42, 8.43, 8.44 and 8.45.

8.51. A separate table No. 8.52 gives the amount of sand movement for fixed low or high pack-aquifer ratios, but different uniformity coefficients of the gravel-pack. From the arrangement in the table, the effect of increasing uniformity coefficient of the gravel pack at low and high pack-aquifer ratios can easily be observed.

8.70. The results of the loss of head readings on the piezometers attached to the model at different points are given in Table Nos. 8.62, 8.63, 8.64 and 8.65. By the arrangement given in these tables it is possible to see how the head loss increases with the velocity for each combination of screen, sand and gravel. The losses were obtained by substracting the manometer reading for piezometer No. 1, from the manometer reading for the piezometer number under which the loss is recorded. All losses are in centimeters of water.

8.71. The discharges at which the various head losses in sand and gravel and the movement of aquifers were measured, were 0.008 and 0.018 cusec. For plotting purposes each discharge was multiplied by 12 to give the discharge for a 6-in diameter well screen, and the values so obtained were then divided by the effective length of the screen to give the discharges in cfs. per foot of 6-in diameter well screen.

* * *

Table 8. (Continued). Results of the Tests of Flow of Sand for (Uniform Gravel Pack-Uniform Aquifer).

Run No.	Gravel Size				Aquifer Size				Pack-Aquifer Ratio Sand moved			
	Sieve	D50	D10	Cu	Slot screen No.	D50	D10	Cu	D50 Gravel	D50 Aquifer	P-A	
		millimeters				mm.			mm.	mm.		grams
[illegible]												
1	1/16"	1.25	1.00	1.23	12-20	1.6	0.3	1.75	1.75	1.3	1.05	-
2	1/8"	3.3	2.30	1.25	12-20	1.4	0.3	1.75	3.8	1.2	2.75	13
3	1/4"	7.5	5.50	1.42	12-20	1.6	0.3	1.75	7.05	1.2	5.05	53
4	1/2"	12.5	10.0	1.25	12-20	1.6	0.3	1.75	10.0	1.2	9.05	98
[illegible]												
5	1/16"	1.25	1.00	1.32	12-20	1.4	0.3	1.75	1.75	1.2	1.05	11
6	1/8"	3.5	2.40	1.25	12-20	1.4	0.3	1.75	3.5	1.2	2.75	33
7	1/4"	7.5	5.50	1.42	12-20	1.4	0.3	1.75	7.05	1.2	5.05	80
8	1/2"	12.5	10.0	1.25	12-20	1.4	0.3	1.75	13.0	1.2	9.05	145

Cu = Uniformity coefficient.
(Screen used with 1/16" size gravel contained 0.04" slot width, and the rest contained 1/8" slot width).

A. 5. (Section 3). Results of the Tests of Flow of Sand for (Uniform Gravel Pack-Uniform Aquifer).

Test No.	Gravel Size				Aquifer Size				Pack-Aquifer Ratio			Sand moved in
	Sieve	D50 mm.	D_{10} mm.	Cu	Sieve screen No.	D_{50} mm.	D_{10} mm.	Cu	D_{50} Gravel mm.	D_{50} Aquifer mm.	P-A	gm.

Discharge through Each [illegible] = .005 cusec
(equivalent to 0.0[illegible] [illegible] per foot of [illegible] [illegible] screen).

1	1/10"	1.85	1.60	1.22	20-30	0.42	0.3	1.4	1.75	0.41	4.3	42
2	1/8"	3.5	2.4	1.55	20-30	0.42	0.3	1.4	3.5	0.41	8.53	53
3	1/4"	7.5	5.5	1.42	20-30	0.42	0.3	1.4	7.05	0.41	17.1	780
4	1/2"	12.3	10.0	1.23	20-30	0.42	0.3	1.4	10.0	0.41	23.1	1380

Discharge through Each [illegible] = .008 cusec
(equivalent to 0.2[illegible] [illegible] per foot of [illegible] [illegible] well screen)

5	1/10"	1.85	1.60	1.22	20-30	0.42	0.3	1.4	1.75	0.41	4.3	75
6	1/8"	3.5	2.4	1.55	20-30	0.42	0.3	1.4	3.5	0.41	8.55	105
7	1/4"	7.5	5.5	1.42	20-30	0.42	0.3	1.4	7.05	0.41	17.1	1500
8	1/2"	12.3	10.0	1.21	20-30	0.42	0.3	1.4	10.0	0.41	23.7	2470

Cu = uniformity coefficient.
(Screen used with 1/10" size gravel contained 0.04" slot width, and the rest contained 1/8" slot width).

6.11 (Section G). Results of the Tests of Flow of Sand
for (Uniform Gravel Packed-Uniform Aquifer).

Ex. No.	Gravel Size				Aquifer Size				Pack-Aquifer Ratio			Sand moved in
	Size	D_{50}	D_{10}	Cu	Size screen	D_{50}	D_{10}	Cu	D_{50} (Gravel)	D_{50} Aquifer	P.A.R	
	in.	mm.	mm.		No.	mm.	mm.		mm.	mm.		gm.

Discharge through Model = 0.004 Cusec (equivalent to 0.014 cusec per foot of 6 in. diameter well screen).

1	1/10"	1.65	1.40	1.32	50-100	0.21	0.155	1.35	1.75	0.2	8.75	73
2	1/8"	3.5	2.4	1.35	50-100	0.21	0.155	1.35	3.3	0.2	16.5	680
3	1/4"	7.5	5.5	1.42	50-100	0.21	0.155	1.35	7.65	0.2	38.2	Continuous movement of
4	1/2"	12.5	10.0	1.23	50-100	0.21	0.155	1.35	10.9	0.2	54.5	Aquifer.

Discharge through Model = .011 Cusec (equivalent to 0.044 cusec per foot of 6 in. diameter well screen).

5	1/10"	1.65	1.40	1.32	50-100	0.21	0.155	1.35	1.75	0.2	8.75	167
6	1/8"	3.5	2.4	1.35	50-100	0.21	0.155	1.35	3.3	0.2	16.5	970
7	1/4"	7.5	5.5	1.42	50-100	0.21	0.155	1.35	7.65	0.2	38.2	Continuous movement of
8	1/2"	12.5	10.0	1.23	50-100	0.21	0.155	1.35	10.9	0.2	54.5	Aquifer.

Cu = Uniformity coefficient.
(Screen used with 1/10" size gravel contained 0.04" slot width, and the rest contained 1/16" slot width).

8.53 (Series D). Results of the Tests of Flow of Sand for (Uniform Gravel Pack-Uniform Aquifer).

Sl. No.	Gravel Size				Aquifer Size				Pack-Aquifer Ratio			Sand moved in
	Size	D_{60} mm.	D_{10} mm.	Cu	Size screen No.	D_{50} mm.	D_{10} mm.	Cu	D_{50} Gravel mm.	D_{50} Aquifer mm.	P-A	gm.
	Discharge Through Model = .008 Cusec (equivalent to 0.054 cusec per foot of 6 in. diam. well screen).											
1	1/16"	1.85	1.40	1.32	60-200	0.17	0.09	1.89	1.75	0.166	10.5	252
2	1/8"	3.5	2.6	1.35	60-200	0.17	0.09	1.89	3.5	0.166	10.8	1050
3	1/4"	7.5	5.3	1.42	60-200	0.17	0.09	1.89	7.05	0.166	42.5	Continuous movement of Aquifer.
4	1/2"	12.5	10.0	1.25	60-200	0.17	0.09	1.89	10.9	0.166	65.5	Aquifer.
	Discharge Through Model = .013 Cusec (equivalent to 0.234 cusec per foot of 6 in. diam. with screen).											
5	1/16"	1.85	1.40	1.32	60-200	0.17	0.09	1.89	1.75	0.166	10.5	235 x
6	1/8"	3.5	2.6	1.35	60-200	0.17	0.09	1.89	3.5	0.166	19.8	1355
7	1/4"	7.5	5.3	1.42	60-200	0.17	0.09	1.89	7.05	0.166	42.5	Continuous movement of
8	1/2"	12.5	10.0	1.25	60-200	0.17	0.09	1.89	10.9	0.166	65.5	Aquifer.

Cu = Uniformity coefficient.

(Screen used with 1/16" size gravel contained 0.04" slot width, and the rest contained 3/32" slot width).

B.12. (continued) Results of the Tests of Flow of Sand for (Uniform Gravel Pack–Non-Uniform Aquifers).

Ex. No.	Gravel Size: Sieve	Gravel Size: D_{60} mm	Gravel Size: D_{10} mm	Gravel Size: Cu	Well-screen slot width	Aquifer Size: D_{60} mm	Aquifer Size: D_{10} mm	Aquifer Size: Cu	Pack-aquifer Ratio: D_{50} Gravel mm	Pack-aquifer Ratio: D_{50} Aquifer mm	Pack-aquifer Ratio: P-A	Sand moved in gms.
	Discharge through holes = 0.023 cusec (equivalent to 0.074 cusec per foot of 6-in diameter well screen).											
1	1/10"	1.85	1.40	1.32	0.04"	1.02	0.24	4.25	1.75	0.83	2.1	–
2	1/8"	3.5	2.6	1.35	3/32"	1.02	0.24	4.25	3.3	0.83	4.0	45
3	1/4"	7.5	5.3	1.42	3/32"	1.02	0.24	4.25	7.00	0.83	8.5	85
4	1/2"	12.5	10.0	1.25	3/32"	1.02	0.24	4.25	11.0	0.83	13.2	210
	Discharge through holes = 0.013 cusec (equivalent to 0.036 cusec per foot of 6-in diameter well screen).											
5	1/10"	1.85	1.4	1.32	0.04"	1.02	0.24	4.25	1.75	0.83	2.1	52
6	1/8"	3.5	2.6	1.35	3/32"	1.02	0.24	4.25	3.3	0.83	4.0	70
7	1/4"	7.5	5.3	1.42	3/32"	1.02	0.24	4.25	7.00	0.83	8.5	97 x
8	1/2"	12.5	10.0	1.25	3/32"	1.02	0.24	4.25	11.0	0.83	13.2	235

Cu = Uniformity Coefficient.

C.45 (Series 3b): Results of the Tests of Flow of Sand for (Uniform Gravel [illegible]-uniform Aquifer).

No.	Size of Gravel				Well-screen slot width (in.)	Size of Aquifer			Pack-Aquifer Ratio			Sand moved in gm.
	Size	D50 mm	D10 mm	Cu		D50 mm	D10 mm	Cu	D50 Gravel/D50 Aquifer	D10	Cu	
	Discharge through model = 0.093 cusecs (equivalent to 0.031 cusecs per foot of 6-in diam. well screen).											
1	1/16"	1.83	1.4	1.32	0.047"	0.5	0.16	3.12	1.75	0.42	4.2	42
2	1/8"	3.3	2.0	1.33	3/32"	0.5	0.16	3.12	3.3	0.42	7.0	45
3	1/4"	7.5	5.3	1.42	3/32"	0.5	0.16	3.12	7.03	0.42	10.0	140
4	1/2"	12.5	10.0	1.28	3/32"	0.5	0.16	3.12	10.0	0.42	23.1	1180
	Discharge through model = 0.213 cusecs (equivalent to 0.284 cusecs per foot of 6-in diam. well screen).											
5	1/16"	1.83	1.4	1.32	0.047"	0.5	0.16	3.12	1.75	0.42	4.2	43
6	1/8"	3.5	2.0	1.33	3/32"	0.5	0.16	3.12	3.5	0.42	7.0	63
7	1/4"	7.5	5.3	1.42	3/32"	0.5	0.16	3.12	7.03	0.42	10.0	370
8	1/2"	12.5	10.0	1.28	3/32"	0.5	0.16	3.12	10.0	0.42	23.1	1030

Cu = Uniformity Coefficient.

8.44 (Series G1): Results of the Tests of Flow of Sand for (Uniform Gravel Pack-Nonuniform Aquifer).

Sl. No.	Size of Gravel: Size	D60 mm.	D10 mm.	Cu	Well Screen Slot Width	Size of Aquifer: D60 mm.	D10 mm.	Cu	Pack-Aquifer Ratio: D50 Gravel mm	D50 Aquifer mm	P-A	Sand moved in gm.
	Discharge through Model = 0.005 Cusecs (equivalent to [illegible] cusecs per foot of 6-in. diameter well screen).											
1	1/16"	1.83	1.40	1.32	0.04"	0.3	0.115	2.62	1.75	0.27	6.5	33
2	1/8"	3.3	2.4	1.35	3/32"	0.3	0.115	2.62	3.3	0.27	12.1	93
3	1/4"	7.3	5.3	1.42	3/32"	0.3	0.115	2.62	7.03	0.27	25.8	890
4	1/2"	12.3	10.0	1.23	3/32"	0.3	0.115	2.62	10.0	0.27	33.5	1670
	Discharge through Model = 0.013 Cusecs (equivalent to 0.234 cusecs per foot of 6-in. diameter well screen).											
5	1/16"	1.83	1.4	1.32	0.04"	0.3	0.115	2.62	1.75	0.27	6.5	79
6	1/8"	3.5	2.4	1.35	3/32"	0.3	0.115	2.62	3.3	0.27	12.1	157
7	1/4"	7.3	5.3	1.42	3/32"	0.3	0.115	2.62	7.05	0.27	25.5	1730
8	1/2"	12.3	10.0	1.23	3/32"	0.3	0.115	2.62	10.0	0.27	33.5	2730

Cu = Uniformity Coefficient.

6.08 (Series B.): Results of the Tests of Flow of Sand for (Uniform Gravel Packed around Aquifer).

No. of Test	Size of Gravel: Size	Size of Gravel: D_{50} mm.	Size of Gravel: D_{10} mm.	Size of Gravel: Cu	Width of screen slot width	Size of Aquifer: D_{50} mm.	Size of Aquifer: D_{10} mm.	Size of Aquifer: Cu	Pack-Aquifer Ratio: D_{50} Gravel / D_{50} Aquifer mm.	Pack-Aquifer Ratio: D_{50} mm.	Pack-Aquifer Ratio: Cu	Sand moved in gm.

Maximum Through Yield = 0.003 Cumec
(Equivalent to 0.034 cusec per foot of Gravel Envelope well screen).

1	1/16"	1.83	1.60	1.32	0.06"	0.24	0.03	2.00	1.75	0.139	10.8	108 g
2	1/8"	3.5	2.6	1.35	3/32"	0.24	0.03	2.00	3.3	0.133	10.7	720
3	1/4"	7.5	5.3	1.42	3/32"	0.24	0.03	2.00	7.05	0.133	42.0 72.0	Continuous movement of
4	1/2"	12.3	10.0	1.25	3/32"	0.24	0.03	2.00	10.0	0.133	84.0	aquifer.

Maximum Through Yield = 0.015 Cumec
(Equivalent to 0.236 cusec per foot of Gravel Envelope well screen).

5	1/16"	1.83	1.60	1.32	0.06"	0.24	0.03	2.00	1.75	0.130	10.8	105
6	1/8"	3.5	2.6	1.35	3/32"	0.24	0.03	2.00	3.3	0.133	10.7	1225
7	1/4"	7.5	5.3	1.42	3/32"	0.24	0.03	2.00	7.05	0.133	42.0	Continuous movement of
8	1/2"	12.3	10.0	1.25	3/32"	0.24	0.03	2.00	10.0	0.130	84.0	Aquifer.

[illegible] Effect of Increasing Uniformity Coefficient of the Gravel Pack

No.	Gravel Size				Aquifer Size				Pack-Aquifer Interface			Sand Flow in
	Size	D60 mm	D10 mm	Cu	Size Screen No.	D60 mm	D10 mm	Cu	D50 Gravel mm	D50 Aquifer Sand mm	P-A	gms
					At Low Pack-Aquifer Ratios							
1	1/8"	3.5	2.4	1.45	12-20	1.4	0.8	1.75	3.3	1.2	2.75	33
2	1/8"	3.9	2.0	1.95	12-20	1.4	0.8	1.75	3.3	1.2	2.75	23
3	1/8"	4.0	1.7	2.4	12-20	1.4	0.8	1.75	3.3	1.2	2.75	25
					At High Pack-Aquifer Ratios							
4	1/8"	3.5	2.4	1.45	60-100	0.21	0.155	1.35	3.3	0.25	13.2	970
5	1/8"	3.9	2.0	1.95	60-100	0.21	0.155	1.35	3.3	0.25	13.2	910
6	1/8"	4.0	1.7	2.40	60-100	0.21	0.155	1.35	3.3	0.25	13.2	350
7	1/8"	3.5	2.4	1.45	60-200	0.17	0.09	1.89	3.3	0.165	19.4	1355
8	1/8"	3.9	2.0	1.95	60-200	0.17	0.09	1.89	3.3	0.165	19.4	670
9	1/8"	4.0	1.7	2.40	60-200	0.17	0.09	1.89	3.3	0.165	19.4	535

8.62. Series A3 Loss of Head Through Sand and Gravel in Model.

(Uniform gravel pack - uniform aquifer).
(Loss of head measured between piezometer indicated and piezometer No. 1, Figure 8.51).

Sl. No.	Gravel Size	Aquifer mesh Screen No.	P-A	Discharge through model in cfs.	Sand moved in gms.	Piezometer No.						
						8	7	6	5	4	3	2
1	1/16"	12-20	1.40	.003	-	18.3	15.1	10.8	7.3	4.1	2.5	0.7
2	1/16"	12-20	1.40	.013	11	27.5	27.0	19.5	11.2	6.7	~~6.9~~ 3.9	0.9
3	1/8"	12-20	2.75	.003	10	10.7	10.6	8.5	6.7	3.5	1.8	0.3
4	1/8"	12-20	2.75	.013	33	17.3	17.0	11.7	8.5	4.9	2.8	0.5
5	1/4"	12-20	5.63	.003	50	6.8	6.3	5.6	4.5	3.2	1.5	0.1
6	1/4"	12-20	5.63	.013	60	10.2	9.9	7.6	5.2	3.0	2.1	0.2
7	1/2"	12-20	9.03	.003	93	4.7	4.6	3.6	2.6	1.5	0.9	-0.1 x
8	1/2"	12-20	9.03	.013	105	6.5	6.5	5.7	4.6	3.3	1.0	-0.1 x

9.33. Series D2 : Loss of Head Through Sand and Gravel in Model.

(Uniform gravel pack - uniform aquifer).
(Loss of head measured between piezometer indicated and piezometer No.1, Figure 9.51).

Ex. No.	Gravel size	Aquifer size Screen No.	P.A	Discharge through model in cusecs.	Sand moved in gms.	Piezometer No. 8	7	6	5	4	3	2
1	1/16"	20-50	4.3	.003	42	22.5	22.3	15.9	9.5	5.2	2.0	0.4
2	1/16"	20-50	4.5	.013	75	37.5	37.1	27.0	17.2	10.5	5.9	1.0
3	1/8"	20-50	8.05	.003	63	12.3	12.0	9.4	6.0	3.0	2.2	0.3
4	1/8"	20-50	8.05	.013	100	21.5	21.1	15.7	10.3	6.1	3.4	0.4
5	1/4"	20-50	17.1	.003	750	9.3	9.1	7.6	5.1	2.2	1.2	0.2
6	1/4"	20-50	17.1	.013	1850	15.7	15.4	12.4	5.4	2.4	1.4	0.4
						Typical Plot, Figure 9.51						
7	1/2"	20-50	23.7	.003	1620	7.3	7.2	5.6	4.4	3.3	1.7	0.1
8	1/2"	20-50	23.7	.013	2470	13.5	13.3	9.0	6.5	3.8	1.9	0.1

6.64. Series G2 : **Loss of Head Through Sand and Gravel in Model.**
(Uniform gravel pack - uniform aquifer).
(Loss of head measured between piezometer indicated and piezometer No. 1, Figure 9.51).

Ex. No.	Gravel size	Aquifer size Screen No.	P-A	Discharge through model in cusec.	Sand moved in gm.	Piezometer No. 8	7	6	5	4	3	2
1	1/16"	50-100	8.73	.003	78	33.0	33.6	28.0	13.2	8.7	4.6	0.6
2	1/16"	50-100	8.73	.013	107	73.2	72.8	52.4	32.7	17.8	9.7	1.2
3	1/8"	50-100	16.5	.003	480	22.5	22.2	14.7	11.3	6.3	3.3	0.2
4	1/8"	50-100	16.5	.013	970	45.6	45.1	32.3	21.7	12.7	7.1	0.4
5	1/4"	50-100	33.2	.003	Continuous							
6	1/4"	50-100	33.2	.013	movement of				Manometer Readings changing.			
7	1/2"	50-100	54.5	.003	Aquifer.							
8	1/2"	50-100	54.5	.013								

9.65. Series D_2 : **Loss of Head Through Sand and Gravel in Model.**

(Uniform gravel pack - uniform aquifer).

(Loss of head measured between Piezometer indicated and piezometer No.1, Figure 9.51).

Sl. No.	Gravel size	Aquifer size Screen No.	P-Δ	Discharge through model in cusec	Sand moved in gms.	Piezometer No.						
						8	7	6	5	4	3	2
1	1/16"	60-200	10.5	.003	252	47.3	47.3	35.2	22.2	13.9	7.7	0.8
2	1/16"	60-200	10.5	.013	255	85.9	85.3	60.2	35.5	18.1	9.8	1.0
3	1/8"	60-200	19.8	.003	1030	32.5	32.3	24.2	15.1	8.2	4.5	0.2
4	1/8"	60-200	19.8	.013	1055	59.8	59.4	45.3	27.7	15.2	7.9	0.8
5	1/4"	60-200	42.5	.003)	Continuous							
6	1/4"	60-200	42.5	.013)	movement of			Manometer Readings Changing.				
7	1/2"	60-200	65.5	.003)	Aquifer.							
8	1/2"	60-200	65.5	.013)								

CHAPTER. IX

RESULTS AND DISCUSSIONS

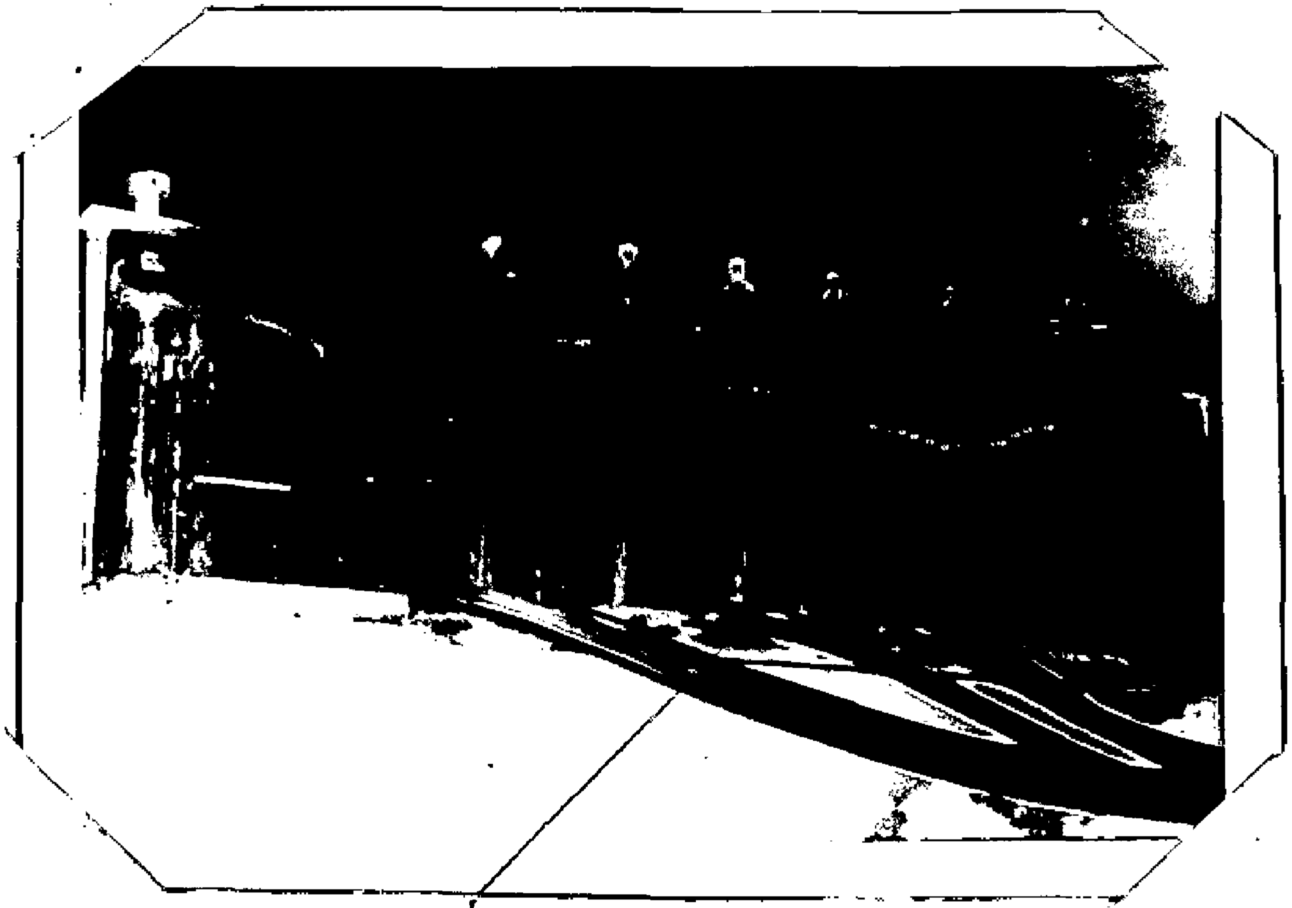
9. RESULTS AND DISCUSSIONS.

9.01. Results of Tests. The results from all combinations of materials, tested in terms of the amount of sand moved during each test and the corresponding head losses, are given in Table Nos. 8.33 to 8.36, 8.42 to 8.45, 8.52, and 8.62 to 8.65. All values of sand moved into the gravel pack are averages for two tests.

9.02. For each group of tests the combinations are arranged in order of the increasing pack-aquifer ratios, and for each sand and gravel combination the results are arranged in the order of the increasing velocities.

9.11. Effect of pack-aquifer Ratios. According to the filtration theory the amount of aquifer that moves into the gravel pack is dependent on the relation of the aquifer particle sizes to the void sizes of the gravel pack. For large pack-aquifer ratios, the gravel pack voids will be large compared to the aquifer particle sizes. Thus the amount of sand that moves into the gravel pack should increase as the pack aquifer ratio increases.

9.12. The theory is confirmed from the tests carried out, for each combination of uniform gravel packs.



CONTINUOUS MOVEMENT OF AQUIFER

FIG. NO. 9.13.

9.21. *Effect of Uniformity Coefficient of Gravel-Packs.* The test data indicates that for any particular P-A ratio, increasing the uniformity coefficient of the gravel-packs causes a decrease in the sand movement.

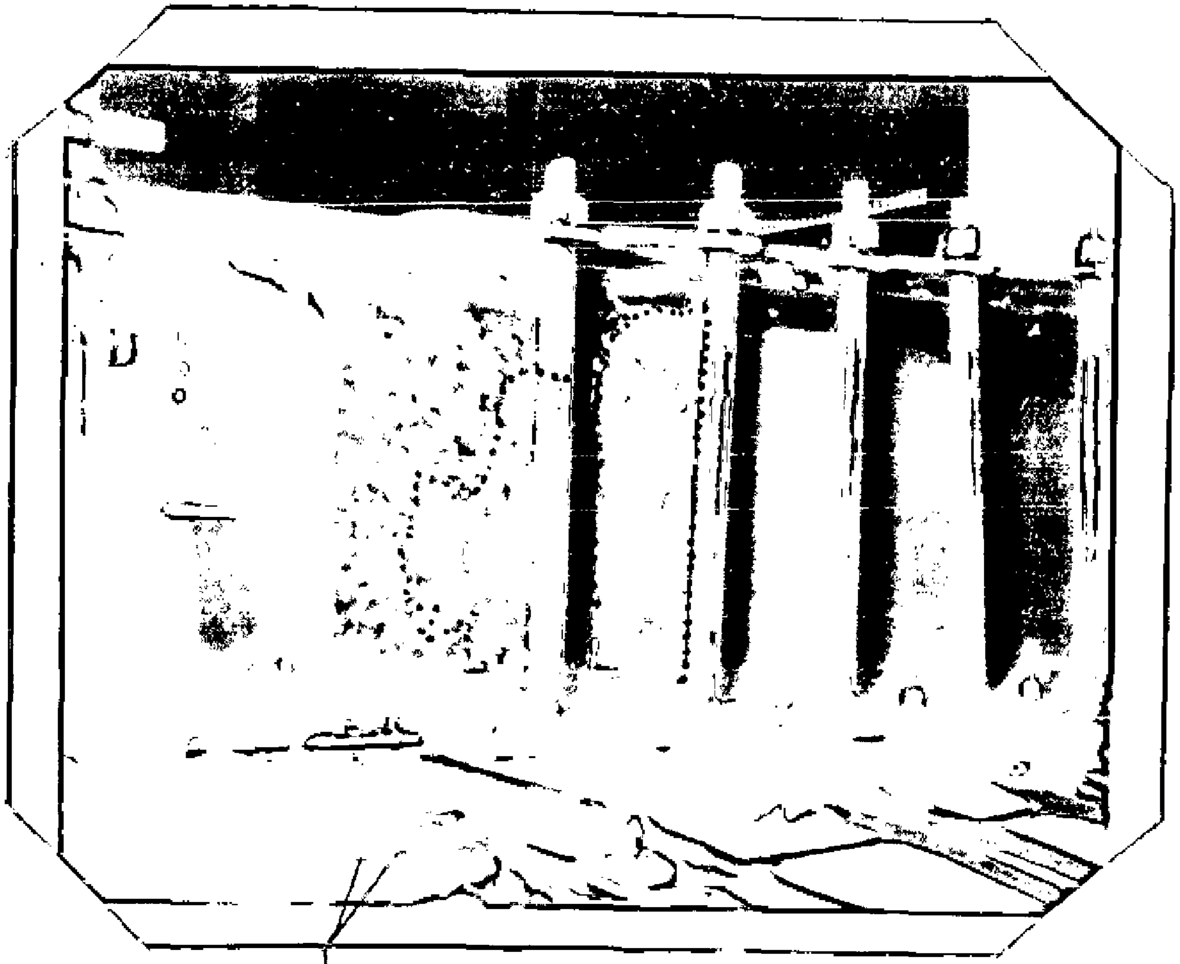
9.22. For low P-A ratios with uniform materials there is only a slight reduction in sand movement with an increase in gravel pack uniformity coefficient.

P-A	Aquifer Uniformity Coefficient.	Gravel Pack Uniformity Coefficient.	Sand moved, gms.
2.75	1.75	1/8" /1.35	33
		1/8" /1.95	26
		1/8" /2.4	25

9.23. For high P-A ratios there is a marked decrease in the amount of aquifer movement due to an increase in gravel pack uniformity coefficient.

P-A	Aquifer Uniformity Coefficient.	Gravel Pack Uniformity Coefficient.	Sand moved, gms.
16.5	1.35	1/8" /1.35	970
		1/8" /1.95	510
		1/8" /2.4	330

9.24. The theory of filtration action predicts that increasing the uniformity coefficient of the gravel packs will reduce the size of the voids and cause a decrease in sand movement. The tests carried out are thus in agreement with the filtration theory.



MOVEMENT OF AQUIFER INTO GRAVEL PACK.

FIG. NO. 9.

the two small samples for a typical test in which the combination was stable.

9.42. It is apparent from the figure that the small sample taken near the centre of the gravel pack has a particle size distribution very similar to the original material indicating that significant movement of the aquifer material has not taken place upto this point within the gravel pack.

9.43. The small sample taken near the interface shows a significant content of the aquifer sizes. The curve for the total gravel pack shows definite evidence of aquifer movement as indicated by the divergence of the lower end of the curve from the curve for the original materials.

9.51. Head Loss Through Models. Referring to figure, for a particular test result of a uniform aquifer with a uniform gravel pack the relative piezometric head distributions are shown. The upper curve shows the manometer readings early in the test, before any surging has been done. The lower curve was taken after the model had stabilized and surging had been done thrice. The lower amount of head loss in the aquifer after surging is largely due to trapped air being removed from the aquifer voids as the test progressed. Also, some fine materials had moved from the aquifer to the gravel pack, increasing the permeability of the aquifer. The head loss in the gravel pack is essentially unchanged, although the small reduction in the head loss within the gravel pack might have resulted from the rearrangement of particles after the surging.

9.52. The data indicates that the loss through the gravel increased when a large quantity of sand was washed into it but since the velocity was also higher when this occured it is not evident how much of the increase was due to each of the two causes.

9.53. The interface between the sand and gravel was normally between the piezometer Nos. 4 and 5, but some deviation from this location occured because it was not possible to tell exactly where the interface would come after the sand and gravel column had been compacted. As is shown by the tables nearly all the loss occured between the upper end of the aquifer compartment, piezometer No. 7 and piezometer No. 4 at the interface.

9.54. For the tests on each combination of sand and gravel, the total head loss through the sand and gravel increases with the velocity. According to Darcy's law the losses should increase in direct proportion to the increase in velocity. The tests indicate that this is approximately true for most of the tests though there are many deviations also.

9.59. The deviations are probably caused by the changes that occured in the sand and gravel. Since the velocity of the water causes a rearrangement of the sand particles and since the magnitude of the change increases with the velocity, the head losses may vary considerably.

9.60. As should be expected, the size of sand particles was the most significant factor in determining the head loss. The size of the gravel and the size of the well screen openings also had some effect as clearly evident from the tests. However, since the head losses through the gravel and the well screen are very small, these were overshadowed by the loss through the sand.

9.61. Uniform and Non-Uniform Gravel-Packs. Although as predicted by the filtration theory and as also confirmed by the tests carried out by Lockman and Halderman, and the U.S. Department of Agriculture (Fort Collins); at a given pack-aquifer ratio non-uniform gravel packs tend to be more effective in preventing aquifer movement than the uniform gravel packs. No tests were, however, run by the author with non-uniform gravel packs or packs containing a gradation of particle size.

9.63. This was decided because of the non-uniform gravel packs having several characteristics that make their use undesirable for tubewells:

(1) It is difficult to place non-uniform gravel packs without segregation of particles even in a laboratory model. When a non-uniform gravel material is shovelled into a well the particles fall through the water column at different velocities according to Stokes Law forming layers with large void spaces on which the smaller particles would finally come to rest. This would create layers of material that would not restrict aquifer movement interspersed with layers of low permeability.

(2) They require a special arrangement and a very careful placement of the gravel material into the annular space of the well, and are thus quite unsuitable especially to the existing placing methods in this country.

(3) The permeability of non-uniform gravel materials, even when placed homogeneously, is lower than uniform materials of the same D_{90} size.

(4) The decreased permeability of the pack causes a increased pumping cost.

SUMMARY OF TEST RESULTS.

9.71. Test results indicate the following values as the upper limits of pack-aquifer ratio for maintaining a stable filtration action.

(a) Uniform Gravel-Pack in combination with uniform aquifer, Limiting P-A ratio = 9.

(b) Uniform Gravel-Pack in combination with non-uniform aquifer, limiting P-A ratio = 12.

9.72. In addition, the data also indicates that

(1) Less aquifer movement occurs with non-uniform aquifers than with uniform aquifers at the same P-A ratio and thus higher P-A ratios are obtainable with non-uniform aquifers as compared to the uniform case.

(2) Increasing the gravel pack uniformity coefficient at any particular P-A ratio decreases sand movement.

(3) Surging reduces head loss at the interface significantly, and its importance in the development of wells in the field cannot be minimised.

9.73. Judgement based on the amount of aquifer moved into the gravel pack indicates that P-A ratios above 9.5 and 13.5 for uniform gravel packs in combination with uniform and non-uniform aquifers respectively, were unstable in the U.S. Department of Agriculture (Fort Collin)'s tests. Whereas ratios of 9 and 12 respectively or less are stable under the author's tests. This is probably due to the difference in velocities of flow in the two cases. The velocity of flow (which may be in the vicinity of 0.1 ft/sec. as safely allowed for actual tubewells in the field) must be considered in selecting the stable P-A ratio.

9.74. A higher limit of the stable pack aquifer ratio has been obtained for uniform gravel packs in combination with non-uniform aquifers as compared with the uniform aquifers. This is in accordance to the tests carried out by Leckman and Haldorman.

9.78. According to the theory advanced by Haldorman, at stable P-A ratios the amount of sand movement is dependent on the unstable portion of the aquifer adjacent to the interface. For an aquifer of high uniformity coefficient this unstable portion may be large because the smallest size fractions in the aquifer will be much smaller than the D_{50} size. For more uniform aquifers the unstable portion may still be larger due to the in-efficient bridging of the aquifer particles.

EXAMPLES OF GRAVEL PACK DESIGN.

9.81. The recommended stable pack aquifer ratios are conservative when used as field design criteria since the velocity of water at the interface was higher during the tests than it usually is in a pumped well.

9.82. Higher pack-aquifer ratios than those recommended showed instability in the laboratory tests. And since gravel packs cannot be placed as carefully in the field as in the laboratory, higher P-A ratios will cause a much greater instability in the field. Therefore, if the design criteria are not followed there is danger of producing a well pumping sand.

9.03. Considering a few examples of gravel pack selection, let the aquifer materials to be gravel packed be defined by the mean diameter in microns and their uniformity coefficients. (Figures 9.04 and 9.05).

Aquifer materials No.	Sizes in Microns D_{50}	D_{60}	D_{10}	Uniformity coefficients	Uniform or non-uniform.
(1)	500	490	330	1.49	Uniform
(2)	150	170	90	1.94	Uniform
(3)	200	330	100	3.30	Non-uniform.

9.04. The particle size distributions are shown in figure. Using only the uniform gravel packs, the results indicate that for uniform aquifers, it should be chosen to give a P-A ratio of 9 or less. Choosing 8.0 as a conservative P-A ratio, sets the D_{50} of the gravel pack at 4000 and 1200 microns for the first two aquifer materials. These gravel packs are plotted in the figure with uniformity coefficients 1.5 and 2.0 respectively, matching that of the aquifers.

9.05. Choosing 11.0 as the conservative P-A ratio for uniform gravel pack in combination with non-uniform aquifer, sets the D_{50} of the gravel pack at 3500 microns for the least aquifer material. This gravel pack is plotted in the figure with a uniformity coefficient of 1.0 and the gradation being approximately parallel to that of the aquifer.

9.36. The well screen should retain at least 90% of the size fractions in the gravel pack. Screens with 0.1-in, 0.08-inch, and 0.02-inch would serve for the three combinations, retaining 96%, 97% and 93% respectively.

9.37. The examples clearly indicate the importance of the size of gravel in the gravel pack and the size of openings of the well screen.

Recommendations for Future Tests.

9.38. Although a large number of tests for different combinations of gravel packs and aquifers were made, the analysis of the results show that additional tests will have to be made before definite conclusions can be drawn for different types of aquifers met in the field.

9.39. The various combinations of sand for the water bearing formation, gravel for the gravel envelope and the size of openings for the screen, were most completely covered for perforated well casings or the slotted tubes. Additional tests will have to be made on screened well casings, and continuous slot well screens, with different sizes of sand and gravel.

9.03. The tests on all the different types of well screens should cover a more complete range of velocities for different sand and gravel combinations.

9.04. The effect of using graded gravels may also be studied but a simultaneous study should be made for the improvement of the placing technique.

9.05. The study of the formation of a natural gravel envelope by surging should also be investigated for a wide range of conditions, so that it could be given as to the conditions for which it is feasible to use this method for producing a gravel envelope.

9.06. The possibility of replacing the gravel envelopes by the use of prepacked well filters need also be studied for simple installations within economical range. The prepack well filter consists of a slotted screen tube with a prefabricated gravel layer of a favourable permeability cemented to it with a special bonding agent.

9.07. In addition, the criteria for the design of well screens, requires the study of the following fundamental problems, and the same need be studied in detail :

(a) What is the loss of head through each well screen operating in clear water with no gravel or sand surrounding the screen.

(b) What effect does placing gravel envelope around the screen has on the loss of head through the well screen.

(c) What effect does size of particles in the gravel envelope has on the loss of head through the well screen.

(d) What effect does variation in discharge has on the loss of head through the gravel envelope and the well screen.

(e) What is the effect of the size of the screen slot openings on the flow of sand into wells.

(f) What is the effect of the orientation of the screen slot openings on the flow of sand into wells and the head loss through the well screen.

(g) What is the best shape of the screen slot openings for a minimum head loss through the well screen and the maximum efficiency of the well.

(h) What is the effect of pH value, the carbonates, the sulphates, and the suspended impurities in the groundwaters on the corrosion of well screens and the formation of incrustations.

(i) How best the corrosion of well screens and the formation of incrustations can be prevented within economical range.

9.33. A more exact study of the design of Gravel

Filters, the thickness of Gravel Packs, and the mechanism involved in the corrosion of well screens and the formation of incrustations, can now best be studied with the help of the latest weapon in the field of sciences, "The Radio-Active-Isotope" or the radio tracer, and efforts should be made for the development of method and equipment for the utilization of isotopes for such research problems

(a) The radio active isotopes are those isotopes whose nuclii spontaneously break up and throw out with greater velocity electrons, heavy particles or electric-waves of short wave-lengths.

(b) The application of radio-active-isotopes is based on the fact that they give off at varying but predictable rates a measurable amount of radiation. The detection and measurement of the radiation which penetrates or is reflected from the material, or the followed complicated path of the tracer material then aid the particular study.

A few studies for the design of sand filters for water supply engineering and the exploration of groundwater storages have already been done in the U.S.A., U.K., and Germany. The study of the design of gravel packs for tubewells can be taken on similar lines. The only thing required is to select a suitable radio-active-isotope for the required experiments, keeping in view its 1/2 life time, the decay constant, and the detectable gamma radiations.

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N.B. ALL THE STATEMENTS MADE IN THE SUMMARY ARE TENTATIVE AS THEY ARE BASED ON A LIMITED NUMBER OF TESTS. ADDITIONAL TESTS WILL HAVE TO BE MADE BEFORE DEFINITE CONCLUSIONS CAN BE DRAWN.

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