SELECTION OF GRAVEL PACK FOR WATER WELLS IN FINE, UNIFORM, UNCONSOLIDATED AQUIFERS

by

John R. Lockman

Carl Rohwer

SELECTION OF GRAVEL PACK FOR WATER WELLS IN FINE, UNIFORM, UNCONSOLIDATED AQUIIFERS

(Progress Report on Performance of Well Screens)

by

John R. Lockman

Carl Rohwer

U. S. DEPARTMENT OF AGRICULTURE

AGRICULTURAL RESEARCH SERVICE

SOIL AND WATER CONSERVATION RESEARCH BRANCH

PROGRESS REPORT

on the

SELECTION OF GRAVEL PACK FOR WATER WELLS IN FINE, UNIFORM, UNCONSOLIDATED AQUIFERS

by

John R. Lockman, Graduate Student
Colorado A and M College
Carl Rohwer, Project Supervisor
Irrigation and Drainage Investigations
Agricultural Research Service

A contribution from the
Irrigation and Drainage Investigations
in cooperation with the
Colorado Agricultural Experiment Station

Fort Collins, Colorado
December, 1954

Prepared under the direction of Dr. Omer J. Kelley, Head, Western Section of Soil and Water Management, Agricultural Research Service

TABLE OF CONTENTS

Progress Report
on the
SELECTION OF GRAVEL PACK FOR WATER
WELLS IN FINE, UNIFORM, UNCONSOLIDATED AQUIFERS(1)

by

John R. Lockman(2)
Carl Rohwer(3)

INTRODUCTION

In the arid regions of the world, ground water is an important source of water for domestic consumption, livestock production, crop irrigation, and industrial uses. It is the only available source of water in some areas. To obtain water from this source, wells must be drilled and pumps must be installed. When the water-bearing formation consists of uniform size sands, it is common well construction practice to place a layer of coarser material between the well screen and the formation. This layer of coarser material is called a gravel pack,(4) gravel envelope, gravel shroud, or a similarly descriptive name. The purpose of this gravel pack is to prevent the movement of the material comprising the aquifer into the well, to increase the capacity of the well, to reduce the pumping lift, and to permit the use of larger openings in the screen. Larger openings reduce the velocity of the water

---

(1) Prepared under the direction of Dr. Omer J. Kelley, Head, Western section of Soil and Water Management, Agricultural Research Service. This report is based on a study of the Performance of Well Screens conducted by Irrigation and Drainage Investigations Section of Agricultural Research Service, in cooperation with Colorado Agricultural Experiment Station and certain well screen manufacturers.
(2) Graduate Student, Colorado A and M College.
(3) Project Supervisor, Irrigation and Drainage Investigations Agricultural Research Service (Retired).
(4) See page 52 for definition of terms.

and the friction losses through the openings. This reduces the danger from corrosion or incrustation, thus insuring maximum life of the well.

When the aquifer consists of sands and gravels of assorted sizes, i.e., well-graded, opinions differ markedly as to the best method of construction. Some contractors with years of experience recommend and practice gravel packing. Others recommend that no gravel pack be placed, but that a screen be selected that will permit much of the finer material of the aquifer to be carried into the well and pumped out, thus forming a layer of coarser material around the screen. This process of forming a "natural gravel pack" is termed development of a well.

Unconsolidated aquifers of fine, uniform material underlie large areas throughout the world. Water wells in these areas must be gravel packed to insure efficiency and reasonable life. In the construction of such a well, three factors must be considered: (a) the character of the aquifer, over which man has no control; (b) the gravel pack which he may select; and (c) the screen which he may also choose. A successful well in a given aquifer depends to a large extent, on the proper design of the gravel pack and screen.

Contrary to the practice of many well contractors, the design of a gravel-packed well must begin with the aquifer, or that factor which cannot be changed, rather than with the slot size of the screen which may be selected. It is the gravel pack which controls movement of the aquifer material. The screen should be chosen to permit the gravel pack to operate most efficiently and to admit water freely into the well. Because of the importance of efficient gravel packs, there is a need for further study of the factors which must be considered in the selection of pack gravels. The results of a study of these factors are presented in the following report.

REVIEW OF LITERATURE

Although gravel packing of water wells has been practiced for about 50 years, very little scientific study has been given to the design criteria for constructing the most effective well in a given aquifer. Much work, however, has been done during the past 30 years or more in relation to gravel filters for use in under-drains, in sewage and water supply filter beds, in protective filters, and in controlling seepage under dams.

Terzaghi (37), in 1921, patented a filter to control the seepage under a dam on a pervious foundation. His criteria were that the 15-percent size of the filter had to be not more than four times as large as the 85-percent size of the finest adjoining layer of soil and at least four times as large as the 15-percent size of the coarsest layer of soil in contact with the filter. Briefly, his criteria may be indicated as follows:

$$\frac{D_{15}\ \text{filter}}{D_{85}\ \text{soil}} \leq 4 \leq \frac{D_{15}\ \text{filter}}{D_{15}\ \text{soil}}$$

The first two terms were selected to prevent particles of soil from passing through the filter. The last two terms were selected to keep the seepage forces within the filter permissibly small. The above criteria have also been suggested for use in designing filters around under-drains and drainage wells.

In 1939, Bertram (6) using uniform sizes of Ottawa sand and crushed quartz found that there was no appreciable washing through of fines so long as the 15-percent size of filter material was not more than 8 to 10 times larger than the 85-percent size of the fine base material. The 15-percent size of the filter material used by Bertram was 10 to 15 times larger than the 15-percent size of the base material. The limiting ratios remained the same regardless of whether the flow was upward or downward and regardless of the magnitude of the hydraulic gradient. No shocks or other disturbing influences were applied to the materials during the test runs. The porosity of the filter material and the sharpness of the grains appeared to be of minor importance in altering the limiting ratios.

The U. S. Waterways Experiment Station reported in 1941 (41) the results of an investigation to determine the minimum grain size of filter materials required to prevent (a) infiltration of fines into the filter material, and (b) infiltration of filter material into various types of commercial under-drain pipe. Laboratory tests were conducted in permeameters and full-scale tests were made using 6-inch diameter under-drain pipes in an outdoor 36-foot flume. In the laboratory tests, flow was downward and visual means were used to detect movement.

From the laboratory study of the filter materials and also from the performance in the flume tests, the following conclusions were reached: (a) a fine material will not wash through a filter material if the 15-percent size of the filter material is less than five times as large as the 85-percent size of the base material; (b) in addition to meeting the first requirement, the grain-size curves for filter and base materials (when plotted on semi-logarithmic paper) should be approximately parallel in order to minimize washing of the fine base material into the filter material. In other words, the ratio of the uniformity coefficients of filter material to base material should be approximately one; (c) filter materials should be packed densely to reduce the possibility of any change in the gradation due to movement of the fines; (d) flow in an upward direction did not increase the danger of failure, unless the seepage pressure became sufficient to cause flotation of the filter; and (e) a well-graded filter material was less susceptible to running through the drain pipe openings than a uniform material of the same average size.

The base material used had a size range of 0.30 down to 0.05 mm, or approximately from a U. S. No. 50 to a U. S. No. 200 sieve, which would include medium, fine, and very fine sands. The uniformity coefficient was 1.75. The 50-percent size was about 0.15 mm.

The following year, in 1942, the U. S. Waterways Experiment Station published a report (40) of an investigation to establish design criteria of drainage wells for several proposed well systems along the Mississippi River levees. The well systems were to control underseepage and to prevent sand boils landward of levees located on pervious foundations. A drainage well to relieve substratum pressures efficiently had to be designed to (a) freely admit water into and out of the well, (b) prevent infiltration of sand into the well after initial pumping, (c) withstand the earth pressures, and (d) resist the destructive action of the water and soil.

In the beginning the study was primarily concerned with the design of drainage wells using commercial brass well screens. However, during the study brass well screens became unavailable commercially, so the design and feasibility of drainage wells with non metallic screens were investigated.

Field and laboratory tests were made on four types of drainage wells, namely: (a) brass well screens, (b) perforated nonmetallic pipes with filters, (c) porous concrete drain pipe, and (d) gravel-filled wells. The tests, both in the field and in the laboratory, consisted of determining (a) the discharge efficiency of various types of wells, (b) the maximum slot or mesh size of brass well screens, and (c) the size and gradation of gravel filters that would safely drain a given foundation sand. Since a brass drainage well system had previously been installed along the toe of Sardis Dam in northern Mississippi, that system was used to study the reduction of substratum pressures and the control of underseepage.

The laboratory tests were performed by installing various wells in different sand foundations contained in a sealed circular metal tank five feet in diameter and two feet deep. Varying pressure heads were then applied at the outer circumference of the sand foundation and the resulting flow of water and inwash of sand measured.

In addition, forty-eight experimental drainage wells were installed parallel to a section of the existing drainage well system of the Sardis Dam well system. The experimental wells were constructed of a variety of materials, including commercial brass well screens, porous concrete pipes, perforated (clay, wood, concrete, iron, and cement-asbestos) pipes with filters, and gravel-filled wells.

Perhaps the most significant finding of the field tests was the successful use of perforated and porous nonmetallic pipes as drainage wells, provided there was a correctly designed filter around the pipe and sufficient perforated area. The criteria used for designing the gravel filters for the perforated pipes were as follows:

$$\frac{\text{15-percent size of filter}}{\text{85-percent size of foundation}} \leq 4 \text{ to } 5$$

$$\leq \frac{\text{15-percent size of filter}}{\text{15-percent size of foundation}}$$

and

$$\frac{\text{15-percent size of filter}}{\text{Perforated opening}} \geq 1.0$$

Both the field and laboratory tests confirmed those criteria.

The gravel filters in the laboratory tests were only 1 1/2 to 2 inches thick. In the field tests all wells were installed by jetting. The brass, iron, and cement-asbestos screens which required filters were installed by first jetting a 6-inch casing to the required depth. Since the screens of that group ranged from 2 to 3 inches in diameter, with most 2 1/2 inches in diameter, the maximum thickness of the gravel was less than 2 inches and in most cases did not exceed 1 1/2 inches. The nonmetallic perforated screens had inside diameters ranging from 4 to 6 inches (also a wooden screen 2 1/2 inches square inside) and were placed inside a 12-inch jetted casing. After accounting for the thick walls, less than 3 inches of gravel filter could be placed around any screen, and less than 2 inches around some.

Little difference in discharge efficiency was found among new brass well screens of the same length, diameter, and openings which had not had an opportunity to corrode or clog. Screen openings as small as 0.008 inch were not found to restrict the flow into the well, if the screen was in clean sand.

Where gravel filters were not used, the following screen opening criterion was established:

$$\frac{\text{85-percent size of foundation}}{\text{Screen opening}} \geq 1.0.$$

The gravel-filled wells showed low discharge efficiencies because of the high frictional resistance to upward flow through the gravel.

In 1947, the Bureau of Reclamation of the U. S. Department of the Interior (39) published the results of its laboratory investigation on protective filters. The test program was conducted to develop criteria for the selection of suitable filter gradations. Layers with different gradations of base and filter materials were compacted in plastic cylinders and subjected to hydraulic heads ranging from 2 to 30 feet. In most tests the compaction of both filter and base material consisted of placing four 2-inch layers of material in the cylinder, each layer receiving 80 firm 9-inch strokes of a 5 1/2-pound hammer. A brass screen with openings depending upon the base material was used as a plane of demarcation between the filter and base layers.

Data were obtained by measurement of the unit flow of water through the assemblies, determination of any change in grain-size distribution which occurred during the test, and by observation or photographs. No head loss measurements were made and most unit flows were very small.

The investigation included filters of uniform grain size and of graded materials. Both uniform and graded base materials were also used. For uniform filters, the following criterion was established:

$$\frac{\text{50-percent grain size of filter material}}{\text{50-percent grain size of base material}} = 5 \text{ to } 10.$$

For graded filters, the following criteria were established:

$$\frac{\text{50-percent grain size of filter material}}{\text{50-percent grain size of base material}} = 12 \text{ to } 58$$

and also,

$$\frac{\text{15-percent grain size of filter material}}{\text{15-percent grain size of base material}} = 12 \text{ to } 40.$$

Sand filters for the treatment of water have been used in Great Britain since early in the nineteenth century and in the United States since late in the nineteenth century (34). The characteristics of filter sands for water treatment have been studied extensively during the past sixty years. However, the results have not been used, to any extent, outside the water treatment field (41). Rapid-sand filters, the type in general use now, have filtration rates as high as 2 gallons per square foot per minute (34). The 10-percent size of the sands ranges from about 0.35 to 0.60 mm and the uniformity coefficient ranges from about 1.2 to 1.7 (8). Uniformity prevents excessive compaction of the sand and promotes even filtration. The function of the gravel in a rapid-sand filter is to support the sand and to spread the wash water over the covering area of each orifice before it reaches the sand and thus to prevent jetting through the sand (8).

The length of useful life of water wells in sands and gravels is of serious concern to engineers responsible for ground water supplies. Bennison (5), in 1946, stated that there is no reason why the average useful life of screened wills should not be 50 years.

Henderson (5), also in 1946, reported that few wells of the ordinary type fail in less than 10 years and the average should be at least 20 years. For artificial gravel-wall wells, half the value of the well is lost in about 15 years. In his experience, very few wells are useful for 40 years.

Millis and Romine (5) gave longevity data resulting from their study of 320 Illinois municipal sand and gravel wells. The records showed that corrosion was not a primary factor of failure. Only 35 of the 320 wells studied were still in service. The average life of the 285 abandoned wells was about 6 years, although some were in use for as long as 45 years. Some failed in less than one year. However, the significant finding of the study was that 98 percent of the failures were caused by screen clogging and incrustation, the result, primarily, of overpumpage.

Gravel packing of wells has been investigated by White (44), Symons (35), and Muskat (25). The problem was also studied by Elizabeth City, North Carolina (31) in connection with the proposed construction of an extensive battery of shallow wells.

Bennison (3) has given four basic principles for designing gravel-packed wells. They are: (a) formations whose 10-percent size is more than 0.010 inch and whose uniformity coefficient exceeds 2.0 do not require gravel packing; (b) the grading of the gravel pack is a function of the 10-percent size of the aquifer, or in other words, the 10-percent size of the gravel pack lies between certain limits with relation to the 10-percent size of the aquifer; (c) the uniformity coefficient of the gravel pack is related to the uniformity coefficient of the formation and is usually 2.0 or less; (d) the thickness of the gravel pack should range from a minimum of 3 inches to a maximum of 12 inches.

Smith (32) selected the ratio of the 50-percent size of the gravel to the 50-percent size of aquifer material as the basis for design of gravel packs. He named the ratio the "gravel-pack ratio." The principal value of his article is that it reports the field results of gravel-packed wells. The Illinois State Water Survey, for which Smith is an engineer, has been gathering sieve analysis data of both the aquifer and the gravel pack in newly constructed wells. At the time of writing, in 1953, data were in hand on about 20 wells. Well effectiveness tests were conducted whenever possible by making interference measurements in nearby wells. "Well effectiveness" was defined as the ratio of the calculated drawdown, based on the observation well data, to the actual drawdown.

His conclusions were that when the gravel-pack ratios were between 4 and 5, wells have an effectiveness of from 90 to 120 percent. When the ratios are smaller, the wells have somewhat less effectiveness. Wells with ratios of from 7 to 10 are considerably less effective. One well with a ratio of about 10 had an effectiveness of only 32 percent. When ratios exceeded 10 appreciably, the wells produced considerable quantities of sand. A well with a ratio of 20 was a complete failure because it produced so much sand.

He also found that a uniform gravel pack was effective even when the particle size of the aquifer material covered a large range. In one case, the uniformity coefficients of the aquifer and gravel pack were 8.3 and 1.5, respectively; the gravel-pack ratio was 5.1.

The well produced no sand. Smith's conclusion is: "In case of doubt, use a finer gravel, rather than a more coarse one."

Leatherwood (16), in 1952, found that the maximum ratios of particle sizes for complete stability were as follows:

$$\frac{D_{15}\ \text{gravel}}{D_{85}\ \text{sand}} < 4.1\ ; \quad \frac{D_{50}\ \text{gravel}}{D_{50}\ \text{sand}} < 5.3$$

In his study, instability was determined by decreasing values in the rate of change of h/D_s as Reynolds number increased, where h was the head loss at the interface, and D_s the mean diameter of the sand. He considered this criterion to be more sensitive than that used by other investigators.

Reynolds number is generally used to determine the character of flow of water through granular material (38). Reynolds number is written

$$R = \frac{Vd\rho}{\mu}\ ,$$

where V is a velocity; d is a length; ρ is density; and μ is the dynamic viscosity. When Reynolds number is applied to the flow of water through a sand or gravel, V is the bulk velocity which is the rate of discharge divided by the cross-sectional area of the material; d is any reasonable average diameter of the sand or gravel grains, according to Muskat (25); ρ is the density of the water; and μ is the dynamic viscosity of the water.

Muskat (25) has suggested that a Reynolds number of one be the upper limit of laminar flow in granular material even though the results of experimenters have given values reaching as high as 12. Tolman (38) has suggested that a Reynolds number of 10 be used as indicating the inception of turbulent flow through granular material. It would not seem contradictory, then, to consider flow in granular material as being laminar at Reynolds number not exceeding one, as being in a transition state at R = 1 to 10, and as being turbulent at values of R exceeding 10. Tolman (38), and many others, have pointed out that ground water moves through granular material in laminar flow, and virtually never as turbulent flow. However, both Tolman and Muskat state that turbulent flow undoubtedly occurs in many aquifers adjacent to a well.

Darcy's Law (38) states that the velocity of moving water in water bearing materials can be determined by the following formula:

$$V = \frac{kh}{\ell} \quad \text{or} \quad V = k \sin \theta$$

in which V is the bulk velocity of the water h, the difference in head at the two ends of the column of material through which the water is moving; ℓ, the length of the column; θ, the angle of water-table slope or slope of the pressure surface of confined water; and k, the coefficient of permeability. For each material k is a constant and must be determined experimentally. This law is applicable only to laminar flow at or near saturation. Further, according to Terzaghi (37), Darcy's Law is applicable only when the volume and shape of the passages are independent of pressure and time.

The criteria recommended by different experimenters for the selection of gravel filters vary appreciably. The range is due to several factors, which are: (a) character of sands and gravels used; (b) compaction of materials preparatory to testing; (c) hydraulic gradient applied; (d) length of time of runs; (e) rate of flow of the water; and (f) the purpose of the filter. A scientific study of the design of gravel packs is complicated by the fact that flow in the aquifer adjacent to the gravel pack and in the gravel pack itself may be laminar or turbulent, or a combination of laminar and turbulent.

from a series of such wells, in which only the particle size of the gravel pack was varied, would make the selection of gravel pack criteria quite easy. Obviously, the cost of such a program would be very high. Only the most skillful well drillers could be used and very close supervision would be needed.

A less expensive method is to construct the screened portion of a well in a tank in which a gravel pack and a sand representing the aquifer could be placed around the screen. This method was originally used in the study of well screens at Colorado A & M hydraulics laboratory, but abandoned because of the prohibitive cost caused by the amount of time consumed in changing and placing the large quantities of sand and gravel.

This investigation is based on the study of a horizontal, cylindrical section of a well containing aquifer, gravel pack, and well screen, in which the flow lines were parallel. In an actual well, the flow lines are radial; however, the advantages of using an apparatus in which the flow is radial were outweighed by the convenience of the cylindrical apparatus. It is believed that the data from the cylindrical

METHODS AND MATERIALS

The ideal method of investigating design criteria of gravel-packed wells is to construct full size wells in an aquifer which could be described accurately as to uniformity of particle sizes, porosity, shape of particles, permeability, and cross-section. If proper construction methods were used, the data obtained from a series of such wells, in which only the particle size of the gravel pack was varied, would make the selection of gravel pack criteria quite easy. Obviously, the cost of such a program would be very high. Only the most skillful well drillers could be used and very close supervision would be needed.

A less expensive method is to construct the screened portion of a well in a tank in which a gravel pack and a sand representing the aquifer could be placed around the screen. This method was originally used in the study of well screens at Colorado A & M hydraulics laboratory, but abandoned because of the prohibitive cost caused by the amount of time consumed in changing and placing the large quantities of sand and gravel.

This investigation is based on the study of a horizontal, cylindrical section of a well containing aquifer, gravel pack, and well screen, in which the flow lines were parallel. In an actual well, the flow lines are radial; however, the advantages of using an apparatus in which the flow is radial were outweighed by the convenience of the cylindrical apparatus. It is believed that the data from the cylindrical apparatus are applicable to actual well conditions. Furthermore, since the interface between the aquifer sand and the gravel pack is the critical section, the importance of reproducing radial flow is greatly reduced.

The equipment used in this study was constructed so that different sand-gravel combinations might be tested. The test apparatus and the test procedure were designed so that measurements of discharge, piezometric heads in both the sand and the gravel, the amount of sand moved, and the water temperature could be made.

Equipment

The apparatus used in this investigation is shown in Figure 1. The plastic cylinder was 37 3/16 inches long with an outside diameter of approximately six inches, and an inside diameter of 5.73 inches. The inside cross-sectional area was 0.179 square foot. Metal end caps with rubber gaskets cemented into recessed rings fitted the ends of the cylinder. The end caps were held snugly against the cylinder ends by four steel rods with wing nuts. One end cap had a 3/4-inch hose connection, to which the water supply hose was connected. The other end cap was fitted with a short length of a 3/4-inch outlet pipe and a regulating globe valve.

The plastic cylinder had 15 piezometer taps. These taps were made of 1/8-inch (I.D.) brass tubing and were set flush with the inside wall of the cylinder. The taps that entered the cylinder wall opposite

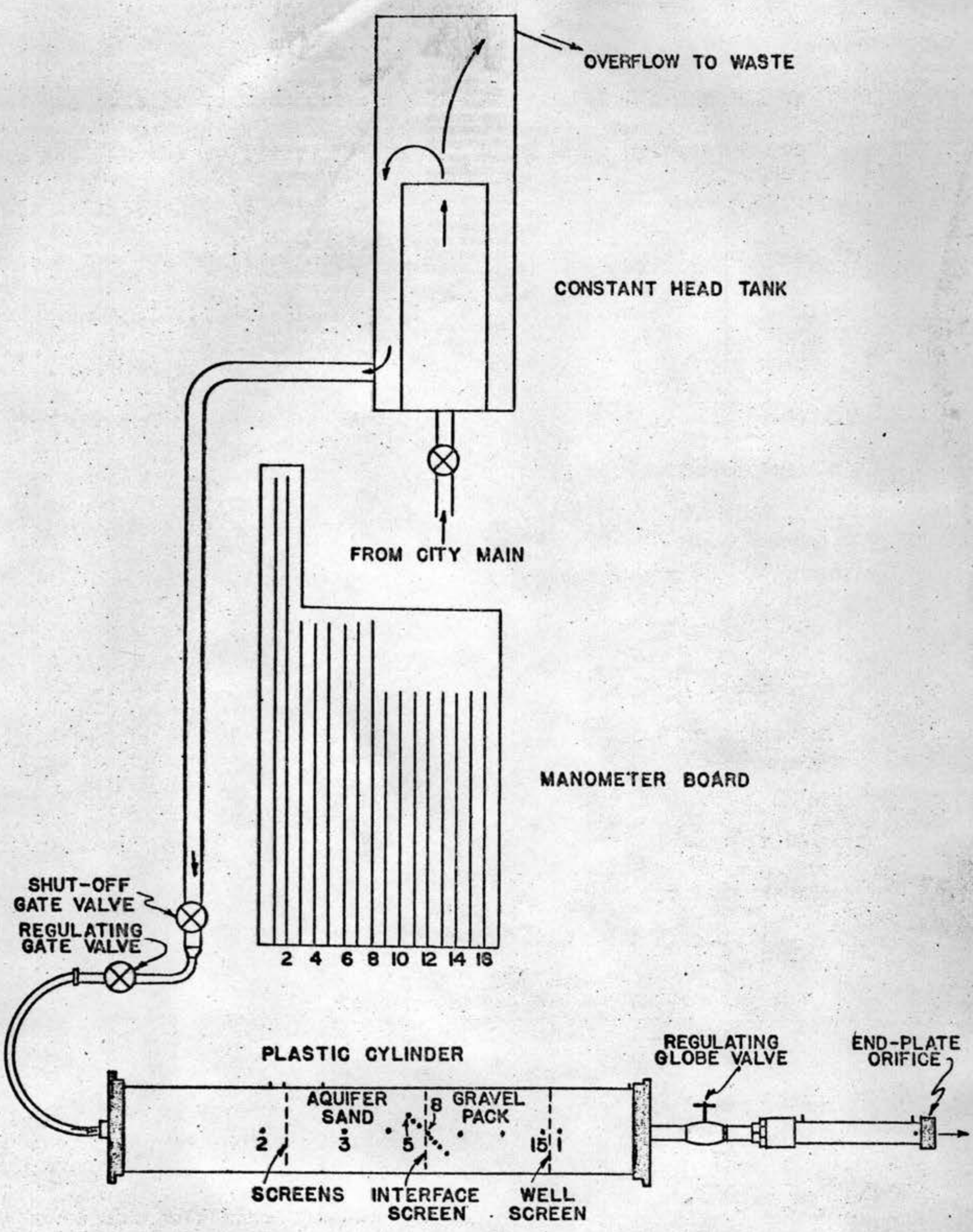


FIG. 1.-Diagrammatic sketch of apparatus.

the sand had fine brass mesh screens soldered on their inner end to keep the sand in the cylinder. Along the top of the cylinder there were four additional taps which permitted air to escape when water was first turned into the cylinder. The wall of the cylinder was strengthened at each tap by a small plastic boss. Plastic screen stops were welded to the inside wall of the cylinder to act as the support of the screens separating the water reservoir portion of the cylinder from the aquifer sand portion. Two set screws entered the cylinder downstream from the pack-aquifer interface. These screws, located 180 degrees apart around the cylinder, prevented the pack-aquifer interface screen from tipping appreciably when the gravel pack was removed from the cylinder.

The main manometer board contained sixteen 11 mm (OD) glass tubes held in place against standard cross-section paper by a wooden strip under the lower end and by copper wires at required intervals around the tubes and through the board. The cross-section paper had 1/10-inch divisions. Inserted into the lower ends of the manometer tubes were rubber stoppers with brass nipples passing through the center of each. Rubber tubing connected the piezometer taps in the cylinder to the brass nipples of the manometer tubes on the board. Just below the manometer board, the rubber tubing passed through a clamping device (see Figure 2) which enabled all 15 cylinder manometers to be shut off simultaneously.

A second manometer board, similarly constructed but with only two manometer tubes, was located above the previously described board. The bottom of the second manometer board was situated just a short

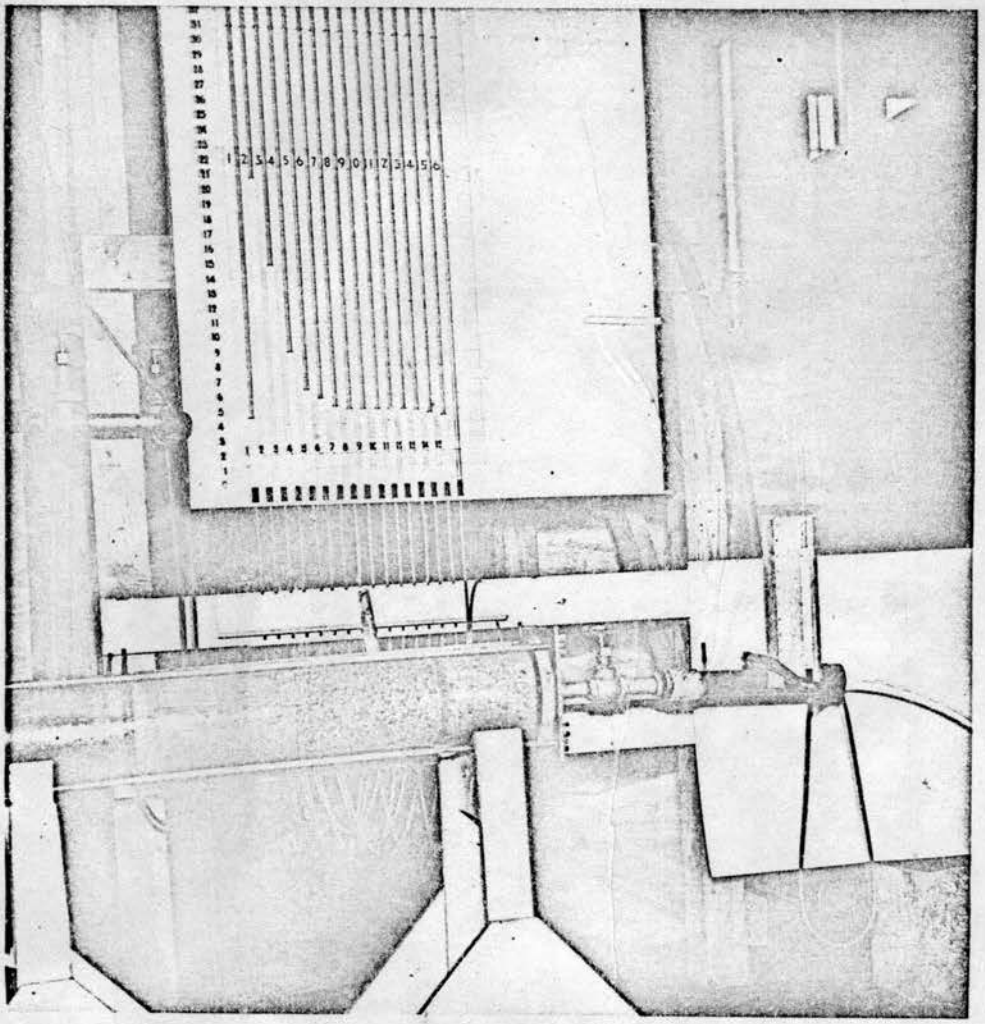


Figure 2.-- Test equipment showing small discharge through end-plate orifice.

distance below the top of the first board, and extended upward to the full height necessary to measure the highest piezometric heads required. No clamping device was used with this board.

The water supply was provided by a constant head tank located about 22 feet above the floor as shown in Figure 1. City water entered the bottom of the tank from a 3/4-inch supply line. The water flowing into the tank had to pass upward through an inner cylinder before it could enter the plastic cylinder supply line. Water left the tank through an outlet on the side of the tank near its bottom or overflowed through a weir near the top of the tank. A 1 1/4-inch pipe ran from the tank outlet down to within convenient distance of the floor and the plastic cylinder. A shut-off gate valve was located in the 1 1/4-inch pipe line within easy reaching distance from the cylinder. The 1 1/4-inch line was then reduced to a 3/4-inch line having a regulating gate valve. Water was carried from the 3/4-inch line to the plastic cylinder in a short length of 3/4-inch rubber hose.

The rate of flow was measured with a calibrated end-plate orifice. The orifice assembly was screwed onto the 3/4-inch outlet pipe of the plastic cylinder. The assembly consisted of pipe bushings for increasing the pipe size from 3/4-inch to 1 1/4 inches, a 1 1/4-inch coupling, a 10-inch length of 1 1/4-inch diameter pipe with a disk of copper screen soldered across its upstream end, and the orifice plate cap.

The orifice pipe had a piezometer tap of 1/8-inch (ID) brass tubing 1 1/4 inches from the outlet end. A rubber tube connected the orifice piezometer tap to the sixteenth manometer tube on the manometer board (Figure 2). When the rate of flow was too small to register on the manometer board, a small manometer was clamped to the orifice pipe, as shown in Figure 2. Two additional taps on the top of the orifice pipe permitted air to be released.

Because of the range of discharges, four different orifice plates were used. Each orifice plate was made from a 1 1/4-inch pipe cap with an accurately machined circular opening in the center. The orifice diameters were 0.181, 0.265, 0.366, and 0.506 inch. Each orifice was calibrated by recording the height of the water column in the orifice manometer at different discharges. The discharge was computed from the time required to supply approximately one hundred pounds of water. The tub receiving the discharged water was placed on a platform scale with one hundred pounds plus the tare weight set on the scale beam. When the scale tipped, the tub was pulled on a steel roller from under the discharging stream. As the stream was cut by the edge of the tub, the time of filling was observed to the nearest one tenth second with a stop watch. The actual time, weight, and manometer readings were used in making the calibration curves in Figures 3, 4, 5, and 6.

In earlier work dealing with the study of well screens (7), (27); discharges were expressed in terms of cubic feet per second per foot of 12-inch diameter screen with a 9-inch gravel pack, or in other words, cubic feet per second per 2.5π square feet of interface area. It was hoped that the results from the plastic cylinder study could be correlated, in a future study, with the earlier work. As a result, it was decided to use discharges in the plastic cylinder tests which would give discharges per unit of interface area that were the same

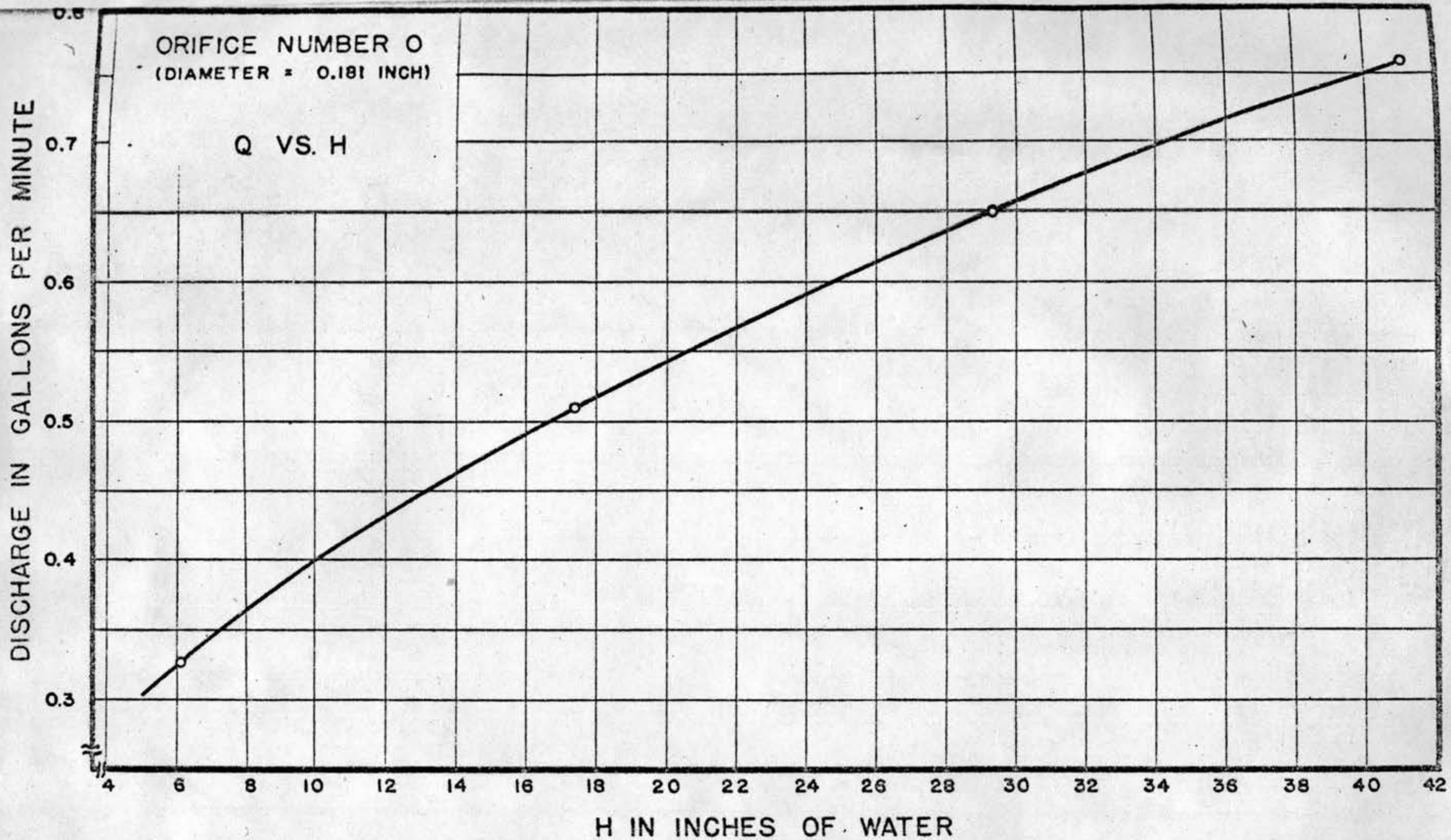


FIG. 3.-Calibration of orifice number zerc.

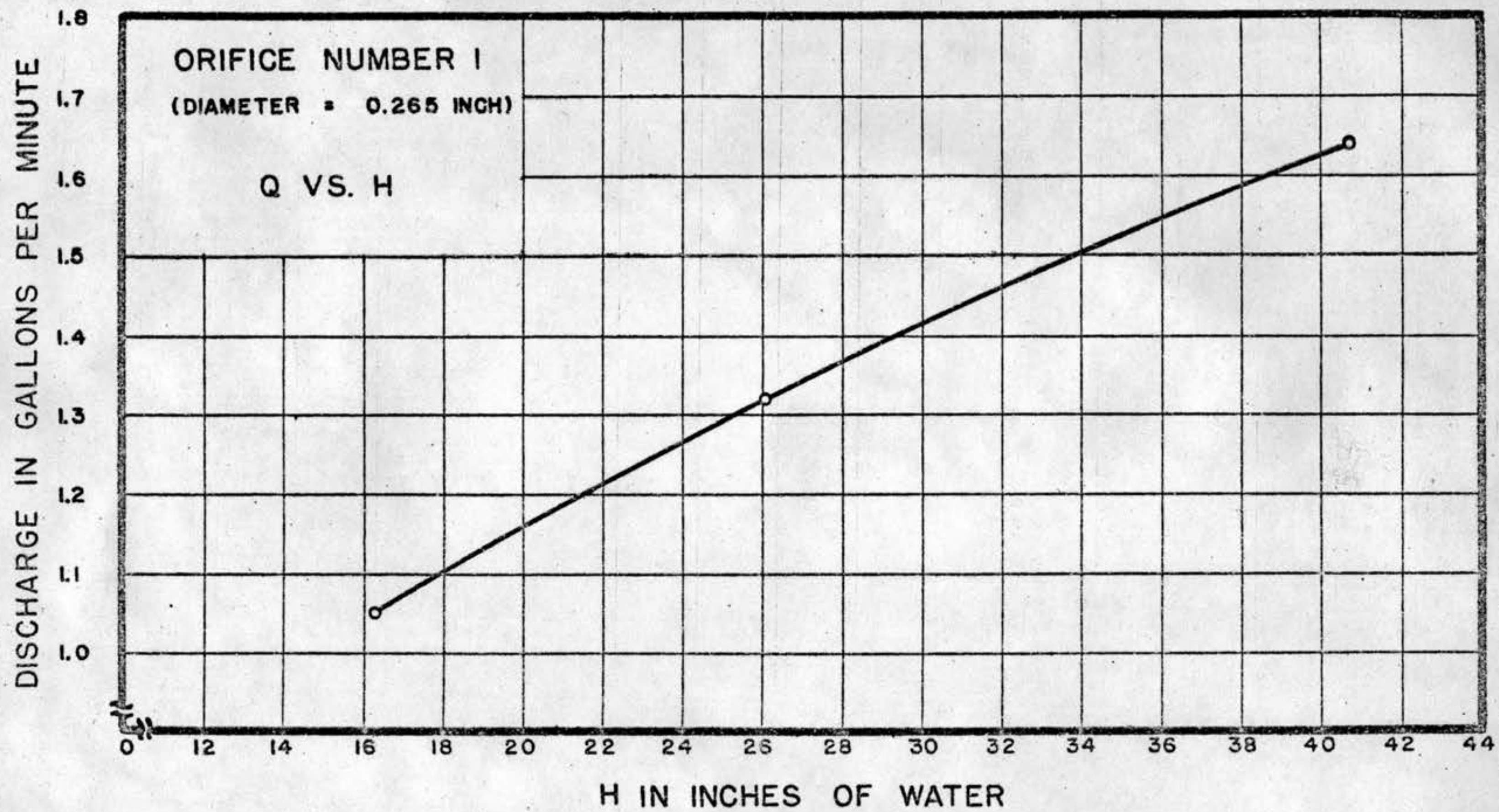


FIG. 4.-Calibration of orifice number one.

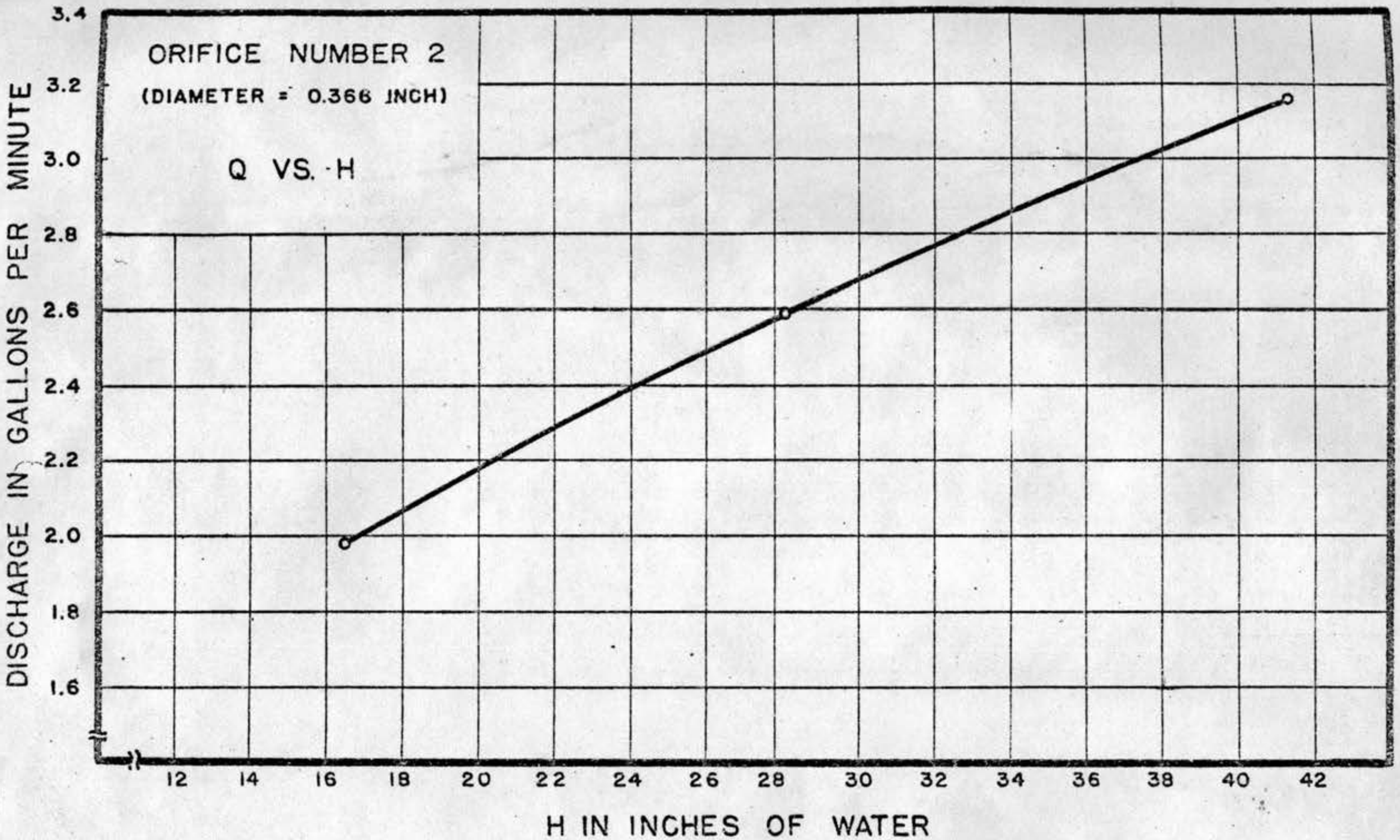


FIG. 5.-Calibration of orifice number two.

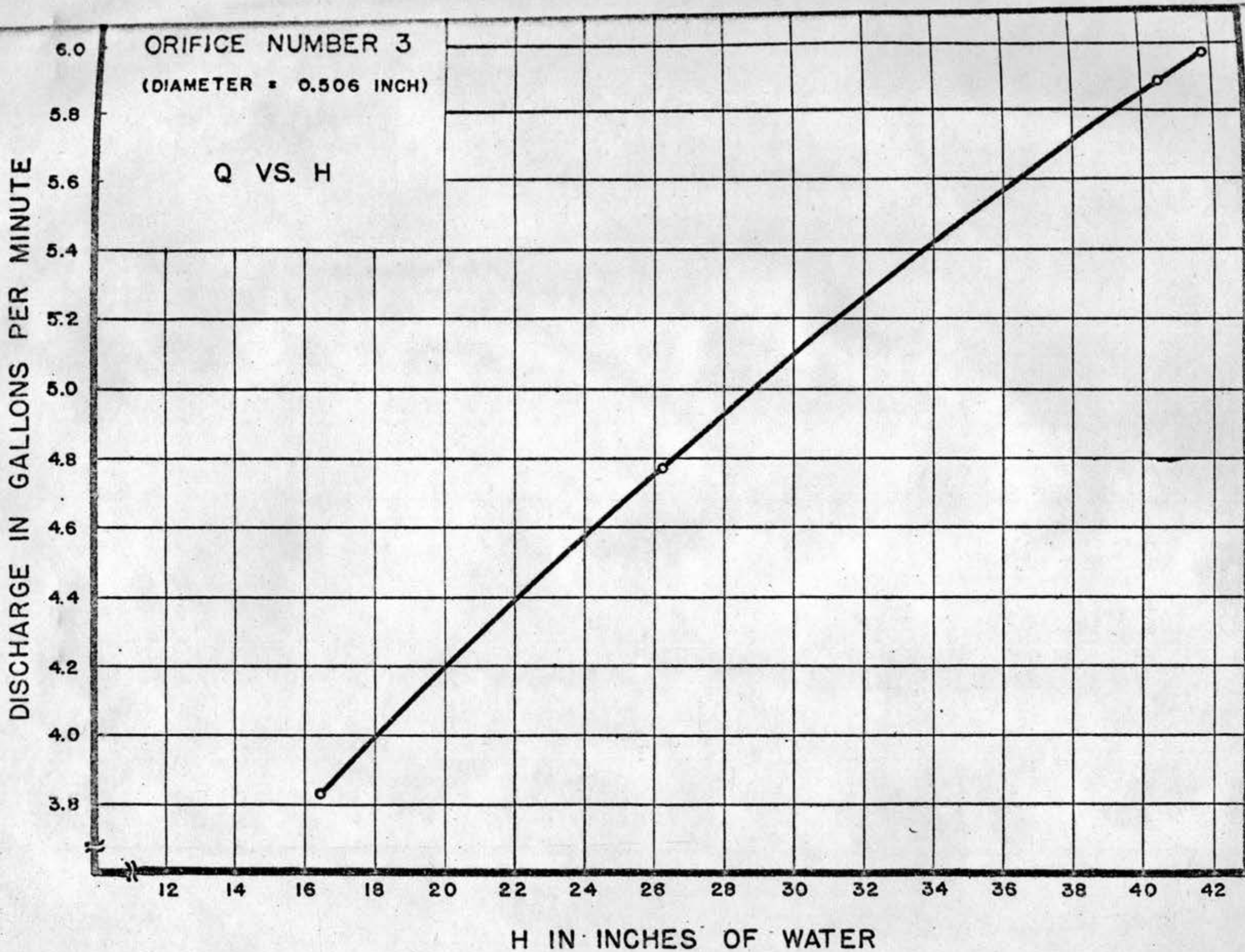


FIG. 6.-Calibration of orifice number three.

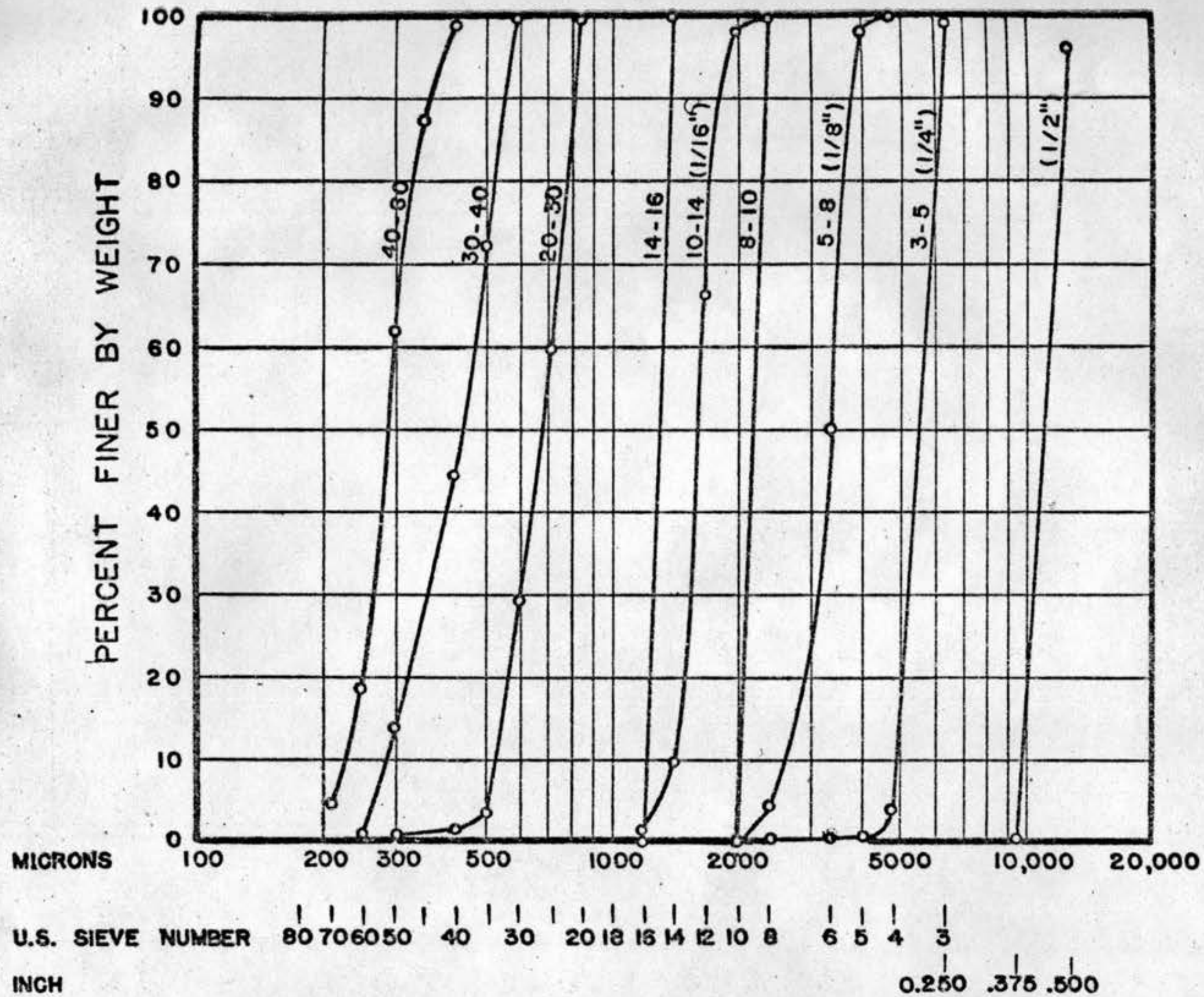


FIG. 7.--Sieve analyses of sands and gravels.

Table 1.--SELECTED PERCENTAGE SIZES AND THE UNIFORMITY COEFFICIENT OF EACH SAND AND GRAVEL.

Sand or Gravel	Percentage size					Uniformity coefficient
	D_{50}	D_{15}	D_{85}	D_{60}	D_{10}	
U.S. sieve numbers or inches	Microns	Microns	Microns	Microns	Microns	$\frac{D_{60}}{D_{10}}$
1/2-inch	11,000	9,900	12,100	11,300	9,750	1.16
1/4-inch	5,500	4,950	6,100	5,650	4,850	1.16
1/8-inch	3,400	2,730	3,680	3,420	2,600	1.32
8-10	2,200	2,080	2,330	2,230	2,030	1.10
1/16-inch	1,600	1,460	1,720	1,630	1,400	1.16
14-16	1,300	1,220	1,380	1,320	1,220	1.08
20-30	680	540	790	720	520	1.38
30-40	435	300	540	465	280	1.66
40-60	290	240	350	300	230	1.30

as in the earlier full-scale screen studies. Therefore, since the cross-sectional area of the plastic cylinder was 0.179 square foot, the equivalent of 1 cubic foot per second, or 448.8 gallons per minute, the prototype discharge would be 448.8 x $\frac{0.179}{2.577}$ or 10.3 gallons per minute in the cylinder. It then follows that 0.50, 0.25, 0.125, 0.0625, and 0.0312 cubic foot per second in the prototype correspond to 5.15, 2.58, 1.29, 0.645, and 0.322 gallons per minute, respectively, in the plastic cylinder.

The sands and gravels used to make up the aquifer and gravel pack were obtained from a local sand pit. The sand and gravel were sieved in the Soil Mechanics Laboratory in standard eight-inch diameter testing sieves. The three following aquifer sands were obtained: (a) 20-30, (b) 30-40, and (c) 40-60. The first number of each pair refers to the U. S. Sieve series number of the sieve which passes the sand and the latter number the U. S. Sieve series number of the sieve which retains the sand. Six gravels were used in making the gravel packs. Designated in the same terms as the sand, they were as follows: (a) 5/8 inch to 3/8 inch, (b) 3-5, (c) 5-8, (d) 8-10, (e) 10-14, and (f) 14-16. Gravels (a), (b), (c), and (e) were called for convenience respectively, 1/2-inch, 1/4-inch, 1/8-inch, and 1/16-inch gravel. To obtain a more accurate knowledge of the particle size distribution of each sand and gravel, samples of each were taken for a complete sieve analysis. Figure 7 shows the sieve analyses of the three sands and six gravels. See also Table 1.

The 50-percent size of each sand and gravel for determining the pack-aquifer ratio was obtained from the sieve analysis. Also, any other percentage size desired was obtained from Figure 7.

The porosities of the sands and gravels were computed by determining the apparent specific gravity and the true specific gravity of samples of each sand and gravel. The porosity was established by using the following relationship:

$$\text{Porosity} = 1 - \frac{\text{Apparent Specific Gravity}}{\text{True Specific Gravity}} .$$

The apparent specific gravity was determined by the volume-weight method. The true specific gravity was determined by using a pycnometer. See Table 2.

The well-screen disks were made from sections of commercial well screens furnished by the manufacturers. The disks were accurately cut and ground so that they made a close fit with the cylinder walls. Figure 8 is a photograph of the different screens used. No attempt was made in the study to analyze the results of the different screens; however, earlier work showed that any reasonable screen had no appreciable effect on the amount of sand moved. That fact was also evident in this study. The characteristics of the well screen are given in Table 3.

Procedure

In preparing for a series of tests, all piezometer and air taps in the plastic cylinder were closed by the use of short rubber nipples having one end plugged with a short piece of brass rod. The valve of the main supply line into the constant-head tank was opened before any other preparations were made. Immediately thereafter, the shut-off

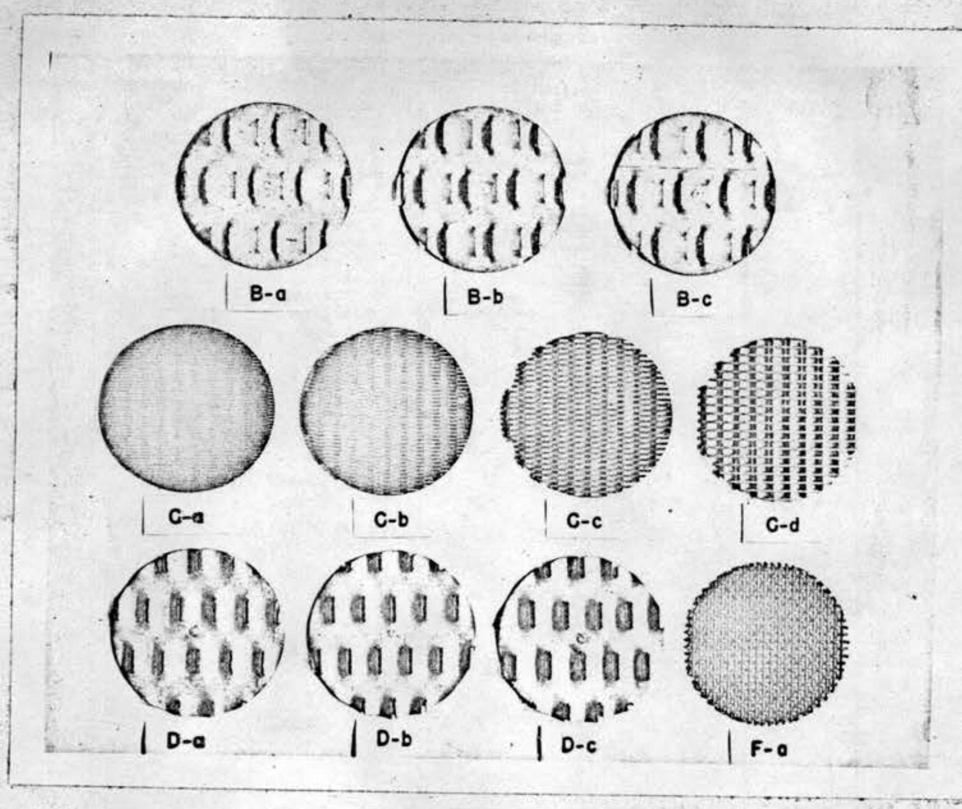


Figure 8.-- Well screen disks used in tests.

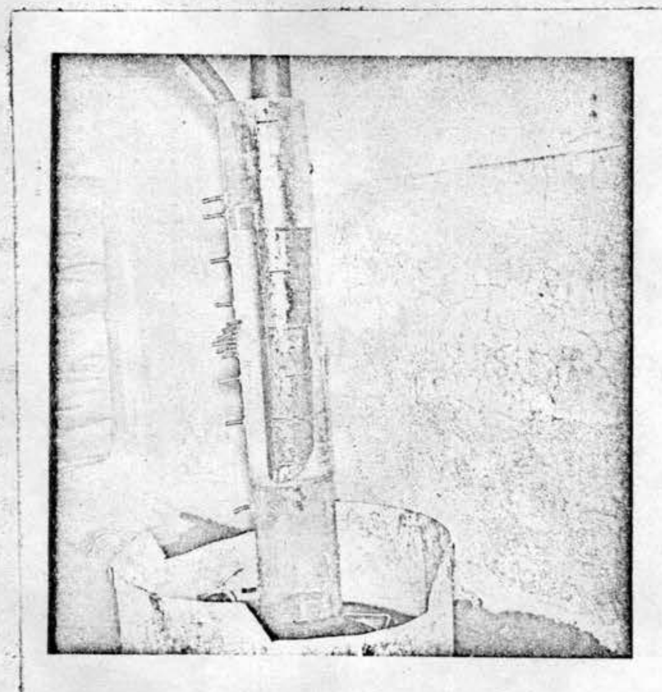


Figure 9.-- Plastic cylinder in upright position for placing sand and gravel.

Table 3.--CHARACTERISTICS OF WELL SCREENS USED IN TESTS.

Symbol	Type	Material	Slot width	Open area
			Inch	Percentage of total surface area
B-a	Twin flow	Galv. iron	1/16	3.46
B-b	Twin flow	Galv. iron	1/8	7.15
B-c	Twin flow	Galv. iron	3/16	11.23
C-a	Continuous slot	Bronze	0.020	18.18
C-b	Continuous slot	Bronze	.040	30.76
C-c	Continuous slot	Bronze	.100	52.63
C-d	Continuous slot	Bronze	0.200	68.96
D-a	Punched slot	Galv. iron	1/16	2.54
D-b	Punched slot	Galv. iron	1/8	4.77
D-c	Punched slot	Galv. iron	3/16	6.67
F-a	Wire mesh	Black iron	0.145	33.64

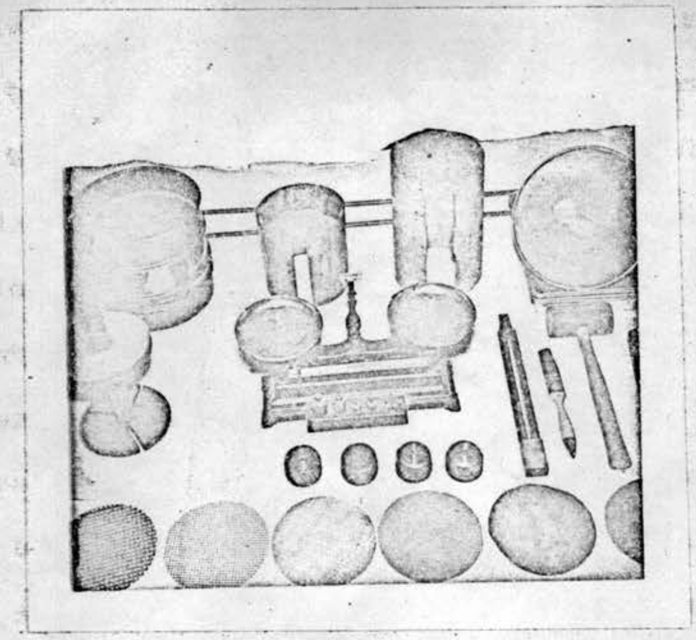
usually possible to make any required adjustment in the volume of sand in the cylinder before the last six taps of the hammer were struck. Very little change in volume occurred after the eighteenth tap of the hammer. The top of the sand was leveled, if necessary, with a wooden tool prepared for the purpose.

An interface screen, was then carefully placed on the surface of the sand. The interface screen was necessary to provide a plane of demarcation between the aquifer sand and the gravel pack. The sizes of the screens are given in Table 1 of the appendix.

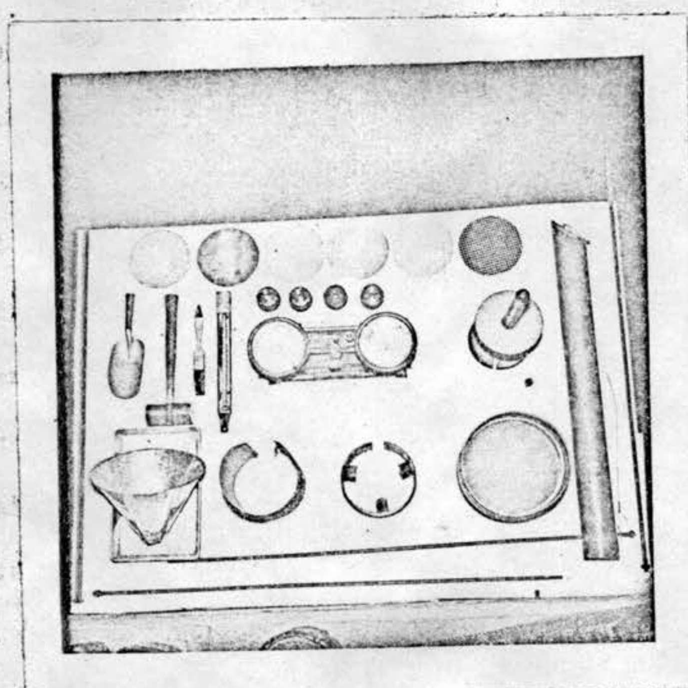
The gravel comprising the gravel pack was placed under water on top of the interface screen. The smaller size gravels were placed by the tremie, while the coarser gravels were placed by using a small hand scoop. The procedure for compacting the gravel was the same as for the sand except that only 18 taps of the hammer were applied for the gravel. The top of the gravel was leveled at the upper edge of the number 15 piezometer tap boss.

A well-screen disk was placed upon the gravel and held in place by an expansive-type sheet metal sleeve (Figure 10).

The water in the cylinder was then drained by removing the plugs from the two bottommost air taps and by breaking the water seal at the base plate. When the cylinder was empty of free water, the cylinder was placed, with its long axis horizontal, on its cradle in front of the manometer board. Next the correct end-plate orifice cap was attached to the discharge end of the orifice pipe. The end caps were tightened against the plastic cylinder ends by screwing up the wing nuts uniformly on the four rods. When the end caps were in place, the



Front view



Top view

Figure 10.-- Accessories and tools used in tests.

regulating valve in the cylinder supply line was closed and the supply hose attached to the hose connections on the inlet end cap. The discharge end of the cylinder was then elevated approximately six inches, as shown in Figure 11. The supply line regulating valve was then opened sufficiently to admit a very small stream into the cylinder. The time of entry of the water was recorded. All four air taps in the cylinder were open while filling took place. Number 1 and 2 piezometer taps were connected to their respective manometer tubes on the manometer board. The orifice manometer was also connected to the orifice tap. As the water reached an air tap, it was permitted to discharge water briefly before being plugged. When water flowed out the orifice, the orifice was partially blocked while the orifice pipe air taps were unplugged and replugged, and while the orifice tap was cleared of air by momentarily removing the manometer rubber tube. The time at which the air was out was recorded.

When all the air had been released the rate of flow was slowly increased until water appeared in manometer tube number 2 on the manometer board and a steady jet was leaving the orifice. For all discharges except the smallest, i.e., 0.322 gallon per minute, the regulating valve in the outlet line was kept fully open. However, for the smallest discharge, in order to get the piezometric heads in the cylinder sufficiently high to register on the manometer board, the outlet regulating valve had to be partially closed. After number 2 manometer registered and the orifice jet became stead, the blocks elevating the outlet end were removed and the cylinder placed

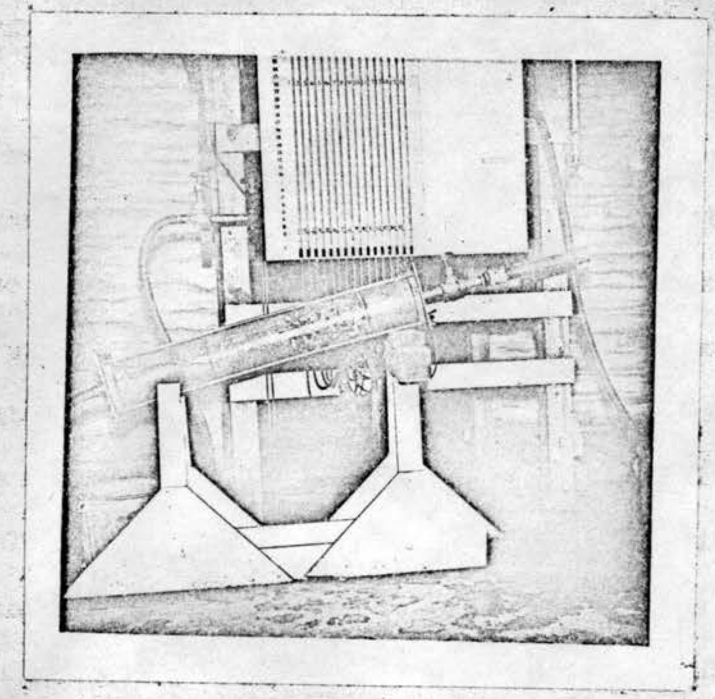


Figure 11.-- Plastic cylinder with discharge end elevated while being filled with water.

horizontally in its cradle. A thermometer was placed in the receiving basin under the discharge jet.

The inlet regulating valve was slowly opened, gradually increasing the rate of flow. The piezometer taps, beginning with number 3, were connected to the manometer board just as soon as the preceding manometer tube registered on the board. The connection was made by removing the piezometer tap plug, permitting water to discharge momentarily, and then hooking up the proper connecting rubber tube. All manometer tubes were connected to the cylinder taps before the desired discharge was reached. The discharge at which the inlet regulating valve was held constant was usually slightly more or less than the desired discharge because the discharge at the end of the run was almost always slightly more or less than at the beginning. The initial discharge which would result in the desired average discharge was learned by experience. The time at which no further changes were made in the inlet regulating valve, at which all manometer tubes registered properly and were steady, and at which the orifice manometer was steady at the desired initial discharge, was recorded as the time of the beginning of the run. Immediately, the end orifice manometer was read to the nearest one hundredth of an inch and the cylinder manometers with the exception of numbers 9 through 14, inclusive, were recorded to the nearest tenth of an inch.

No trouble was experienced in determining whether manometer lines had air in them. Air blocked cylinder manometers were immediately apparent because they did not conform to the regular general pattern shown in Figure 2. Trapped air was removed by squeezing the rubber tubing, lifting the tubing, or disconnecting the tube from the cylinder briefly. Only rarely was the orifice manometer affected by air. In this case, the water level in the manometer would oscillate slightly. This trouble was corrected by removing, briefly, the rubber tubing from the orifice pipe tap and the plugs from the orifice pipe air taps.

Each run was of 30 minutes duration. A minute before the time of the end of the run, the water temperature was recorded by reading the thermometer. At the exact time of the end of the run, the orifice manometer reading was recorded and the cylinder manometer rubber tubes clamped shut. The inlet regulating valve was then slowly closed, and then the shut-off valve was closed. The cylinder air taps, with the exception of the one opposite the sand, were unplugged and the outlet regulating valve closed. The cylinder manometer readings were then recorded to the nearest one hundredth of an inch except when the readings exceeded 50 inches. Readings from 50 to 80 inches were read to the nearest tenth of an inch and when greater than 80 to the nearest half inch.

At the end of the test the wing nuts holding the cylinder end caps were loosened sufficiently to permit the slow drainage of the water from the cylinder into clean buckets placed under both ends of the cylinder. When the water level in the cylinder fell below the level of the inlet opening, the supply hose was disconnected. When drainage was complete, the outlet-end cap was removed from the cylinder, the outlet regulating valve opened, and the water in the orifice pipe drained into the clean bucket under the outlet end of the cylinder. The orifice cap was removed, if necessary, and the orifice cap for the next run put on. The cylinder outlet-end cap and orifice assembly were then put aside. The four rods and the cylinder inlet-end cap were next removed. All manometer tubes were disconnected from the cylinder.

The expansive sleeve and well-screen disk were removed and rinsed in the outlet-end bucket before being put aside. All gravel was removed from the cylinder into the bucket. Finally, the inside of the cylinder which had contained the gravel, and the interface screen were brushed clean with a nylon paint brush. All material removed by the brush was brushed into the bucket. By these means all the gravel pack and all the sand carried into or through the gravel pack were caught in the bucket.

During the next run, the gravel was sieved under water to separate the fine material which had been carried out of the aquifer during the test. The fine material was placed in an aluminum pan and dried in an electric oven. When dry, the fine material was weighed to the nearest tenth of a gram. That weight was recorded as the amount of sand carried into or through the gravel pack.

Under normal conditions, tests were made in a series of three or four runs. The first run was at the smallest discharge, the second at a discharge double the first, the third at double the second, etc.

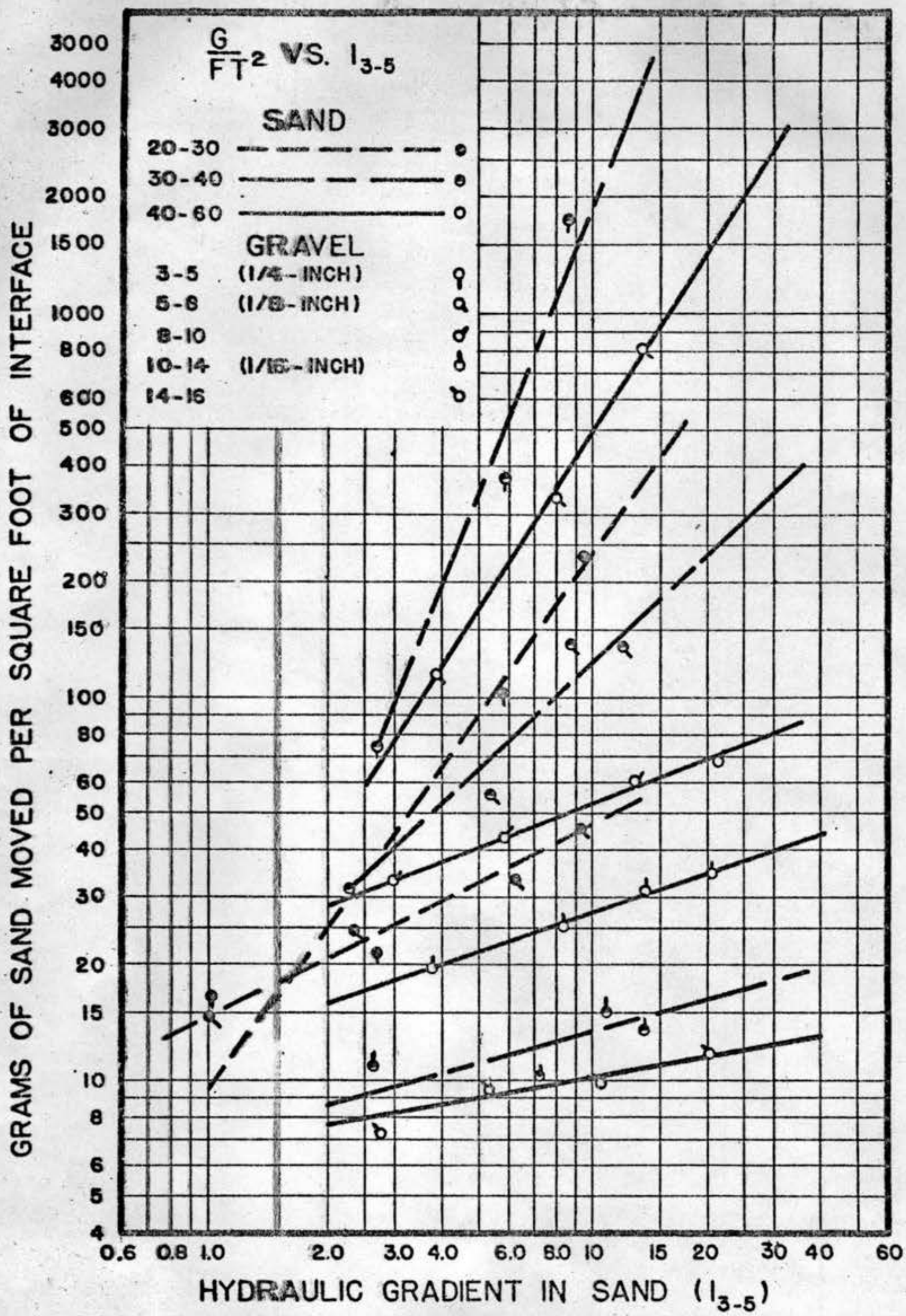


FIG. 14.-Amount of sand moved per square foot of interface versus the hydraulic gradient in the sand between taps 3 and 5 for different sand and gravel combinations. (Log plot).

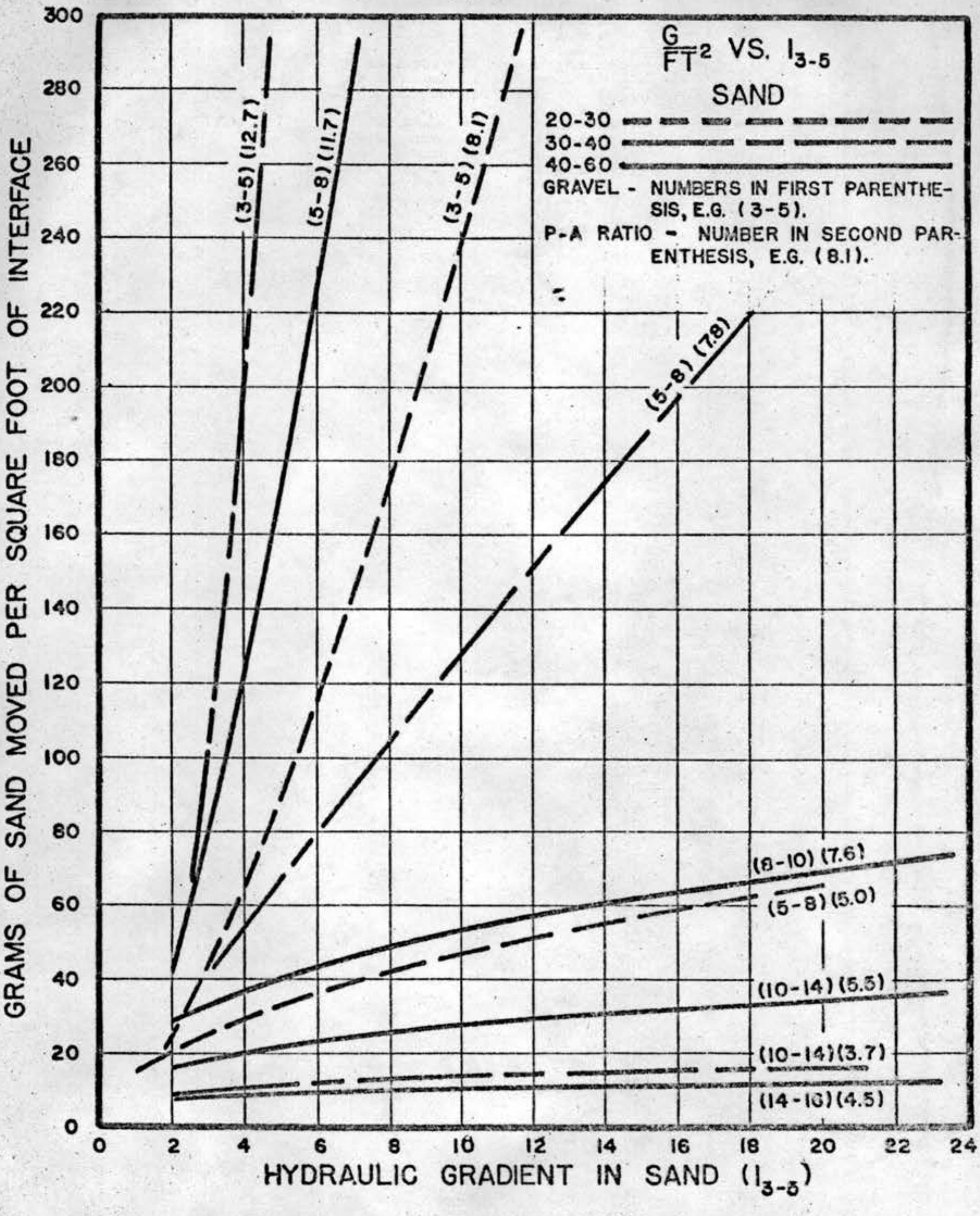


FIG. 15.-Amount of sand moved per square foot of interface versus the hydraulic gradient in the sand between taps 3 and 5 for different sand and gravel combinations.

One sand-gravel combination was used during each series, so that the pack-aquifer was constant throughout the series. Therefore, the sand remained in the cylinder for the series with only a different gravel pack of the same gravel used in each run. The test procedures for each of the runs were the same except for the differences resulting from the sand remaining in the cylinder after the first run.

In preparing the cylinder for any subsequent run, the cylinder was placed upright on the base plate with all taps plugged except those below the sand. Approximately an inch of gravel was placed on the interface screen and then the leveling tool placed on top. Water was then added very slowly to avoid disturbance of the interface. When there were several inches of water above the gravel, the leveling tool was removed and additional gravel placed under water until the required level had been reached. The consolidation of the gravel and subsequent steps were as previously described.

ANALYSIS OF DATA

The control of the movement of the sand into the gravel pack was of primary interest in this investigation. However, the importance of minimum head loss in the pack and maximum slot openings in the screen was not overlooked. For many years engineers have considered the velocity of the water to be an index of the transporting or eroding force. Therefore, the first analysis of the data covered the relationship of the amount of sand moved to the velocity of the water through the sand pores. Figures 12 and 13 summarize this analysis. See also Table 2 of Appendix.

Each point in Figure 12 represents the average of the grams of sand moved and of the average velocity through the sand of all the tests for one sand-gravel combination and one discharge, regardless of the well screen used. The average velocity was determined by dividing the bulk velocity at average discharge by the porosity of the sand. Each line of Figure 12 is the straight line on the logarithmic plot that most nearly fits all points of the same sand-gravel combination. In Figure 13, the lines of Figure 12 are drawn on rectangular coordinate paper.

The second analysis of the data covered the relationship of the amount of sand moved to the drag. Drag is the force exerted by the water upon the sand particles that causes the sand movement. Since the drag is proportional to the hydraulic gradient, the relationship of the amount of sand moved to the hydraulic gradient was investigated. Figures 14 and 15 summarize these data. The ordinate of both figures is the amount of sand moved per square foot of pack-aquifer interface and was determined by dividing the amount of sand moved in the plastic cylinder by the cross-sectional area of the cylinder. The abscissa of both figures is the hydraulic gradient in the sand as measured between piezometer taps 3 and 5, which were 4.44 inches apart.

Each point plotted in Figure 14 represents the average of the grams of sand moved per square foot of interface and the average hydraulic gradient of all the tests for one sand-gravel combination and one discharge, regardless of the well screen used. Each line of Figure 14 is the straight line on the logarithmic plot that most nearly fits all points of the same sand-gravel combination. In Figure 15, the lines of Figure 14 are drawn on rectangular coordinate paper.

The shapes of the curves of the sand moved versus the average velocity and of the sand moved per square foot of interface versus the hydraulic gradient were similar, as shown by Figures 13 and 15. Regardless of the sand-gravel combination, the amount of sand moved increased with increase in velocity and hydraulic gradient. For any one sand, the amount of sand moved at a given velocity varied directly with the pack-aquifer ratio. At the smaller P-A ratios, the rate of increase in the amount of sand moved decreased as the velocity and hydraulic gradient increased. At higher P-A ratios, the amount of sand moved increased at nearly a constant rate as the velocity and hydraulic gradient increased. At the highest P-A ratios, the rate of increase in the amount of sand moved increased as the velocity and hydraulic gradient increased. The major difference in the curves shown in Figures 13 and 15 occurred in the position of the curves of the 20-30 and 30-40 sands at intermediate P-A ratios.

In analyzing the data, all interpretations were based on the trend indicated by the curve that best fitted the points plotted. Each plotted point, in turn, represented the average value of the two coordinates of all test data for the same condition, but regardless of the well screen used. This method of analysis was used throughout this study although individual test data, and even the plotted points of averages, may have deviated from the trend indicated.

The first requirement of an efficient gravel pack is that it must prevent movement of the fines into the pack. Earlier investigators have shown that the ratio of sizes of the particles comprising the aquifer and pack is an important factor in controlling the movement of the fines. For this reason the next analysis of the data in this study was concerned with the relationship between the amount of sand moved and the pack-aquifer ratio. Table 4 and Figures 16, 17, and 18 summarize the data. Each figure is for one sand. The P-A ratio was changed by the use of a gravel of different size. A curve for each of the three or four discharges was drawn. In the finer sands, only three discharges could be tested because of limitation in the available head in the water supply line from the constant head tank. In each of the three figures, the plotted point of the amount of sand moved at the highest P-A ratio and the highest discharge lies beyond the limits of the figure.

For any one sand, the amount of sand moved increased with an increase in the pack-aquifer ratio and with an increase in discharge. At small discharges in the 20-30 sand, the increase in the amount of sand moved with an increase in P-A ratio was very small. However, even at small discharges in the finest sand tested - a 40-60 sand -

Table 4.--GRAMS OF SAND MOVED PER SQUARE FOOT OF INTERFACE VERSUS PACK-AQUIFER RATIO AT DIFFERENT DISCHARGES.

Sand size	Gravel size	P-A ratio	*Q_a = 1.8 gpm/ft^2 of interface		*Q_a = 3.6 gpm/ft^2 of interface		*Q_a = 7.2 gpm/ft^2 of interface		*Q_a = 14.4 gpm/ft^2 of interface			
U.S. sieve nos.	Inches or U.S. sieve nos.		Grams of sand moved	Grams per ft^2 of interface	Grams of sand moved	Grams per ft^2 of interface	Grams of sand moved	Grams per ft^2 of interface	Grams of sand moved	Grams per ft^2 of interface	Grams of sand moved	Grams per ft^2 of interface
			G	$\frac{G}{ft^2}$	G	$\frac{G}{ft^2}$	G	$\frac{G}{ft^2}$	G	$\frac{G}{ft^2}$	G	$\frac{G}{ft^2}$
20-30	1/8-in	5.0	2.6	14.5	4.4	24.6	6.0	33.5	8.1	45.2		
20-30	1/4-in	8.1	3.0	16.8	3.9	21.8	14.0	78.2	27.9	156.	(Q_a 28.6 gpm/ft^2) 88.6	495.
20-30	1/2-in	16.2	4.3	24.0	5.6	31.3	34.1	190.5	109.6	612.		
30-40	1/16-in	3.7	2.0	11.2	1.9	10.6	2.7	15.1	2.4	13.4		
30-40	1/8-in	7.8	5.6	31.3	10.0	55.8	24.9	139.	24.6	137.3		
30-40	1/4-in	12.7	13.2	73.8	67.1	375.	311.8	1740.	--	--		
40-60	14-16	4.5	1.3	7.3	1.7	9.5	1.8	10.1	2.1	11.7		
40-60	1/16-in	5.5	3.5	19.5	4.6	25.7	5.6	31.3	--	--	(Q_a 11.3 gpm/ft^2) 6.3	35.2
40-60	8-10	7.6	6.0	33.5	7.8	43.6	10.9	60.9	12.3	68.6		
40-60	1/8-in	11.7	21.3	119.	59.8	334.	145.4	813.	--	--		

$$*Q_a \text{ in gpm/ft}^2 \text{ interface} = \frac{Q_a \text{ in gpm in plastic cylinder}}{\text{Cross-sectional area of cylinder (ft}^2)} \quad \frac{Q_a \text{ (gpm in cylinder)}}{0.179\text{ft}^2}$$

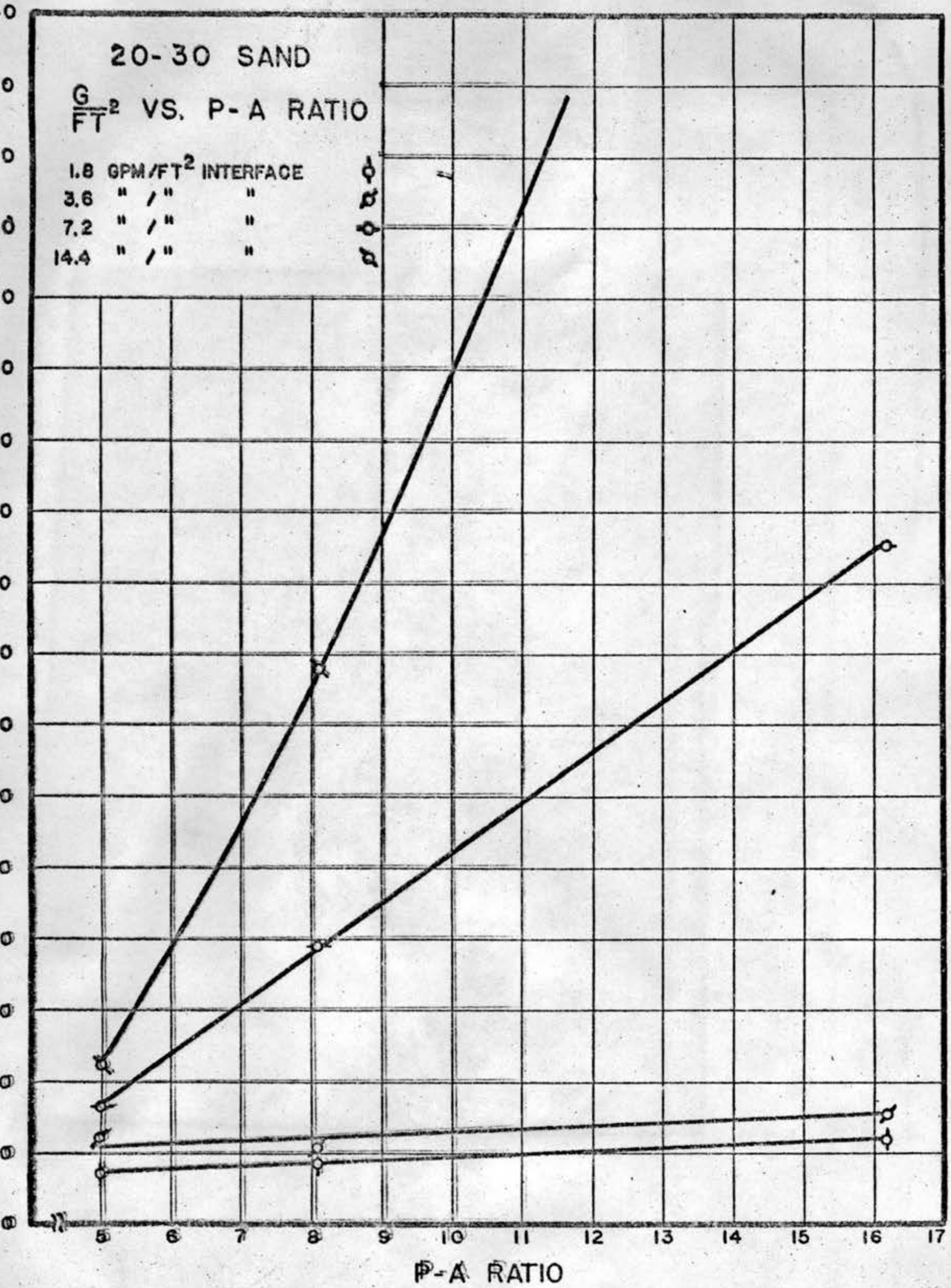


FIG. 16.--Amount of 20-30 sand moved per square foot of interface versus the pack-aquifer ratio at four discharges.

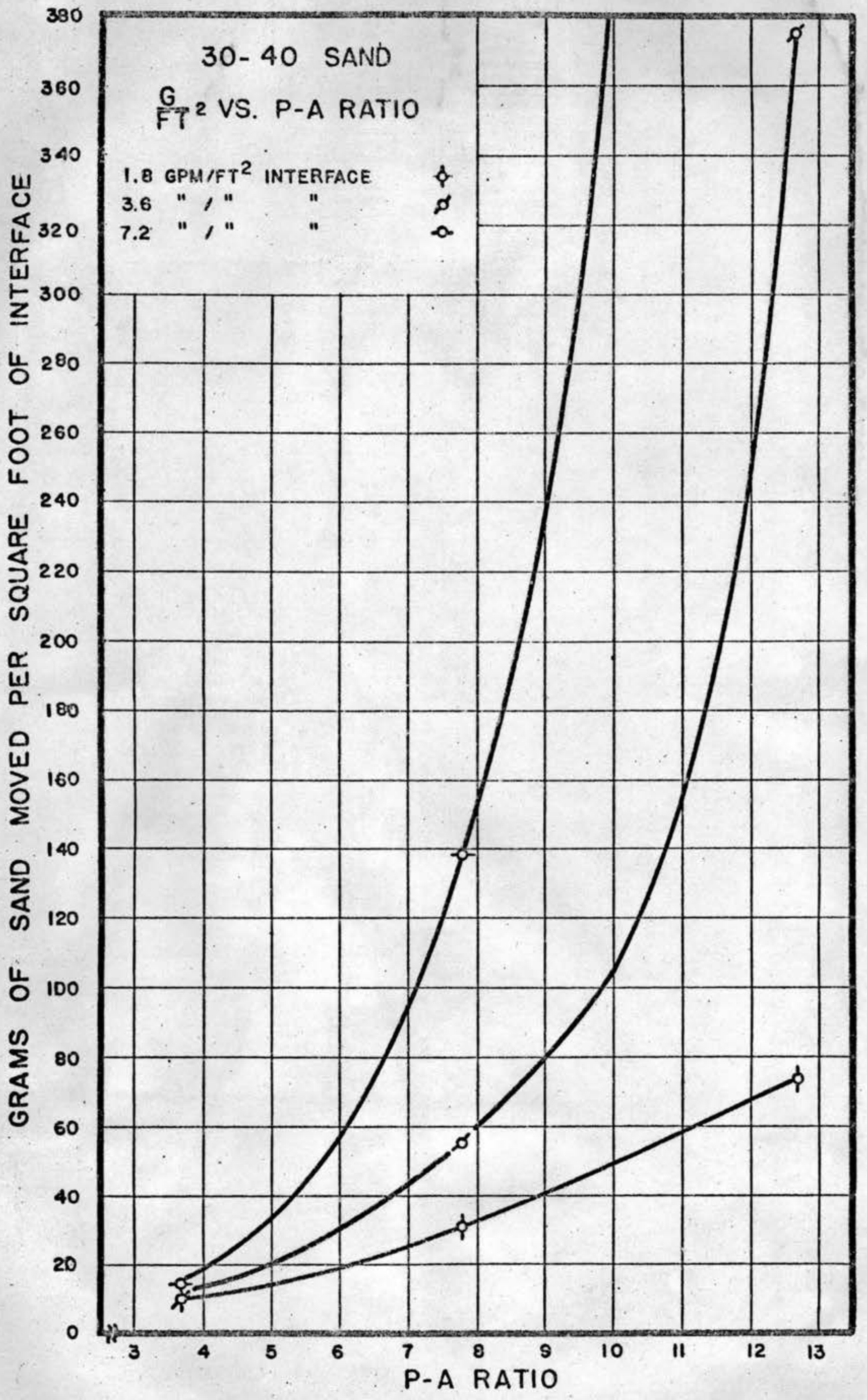


FIG. 17.-Amount of 30-40 sand moved per square foot of interface versus the pack-aquifer ratio at three discharges.

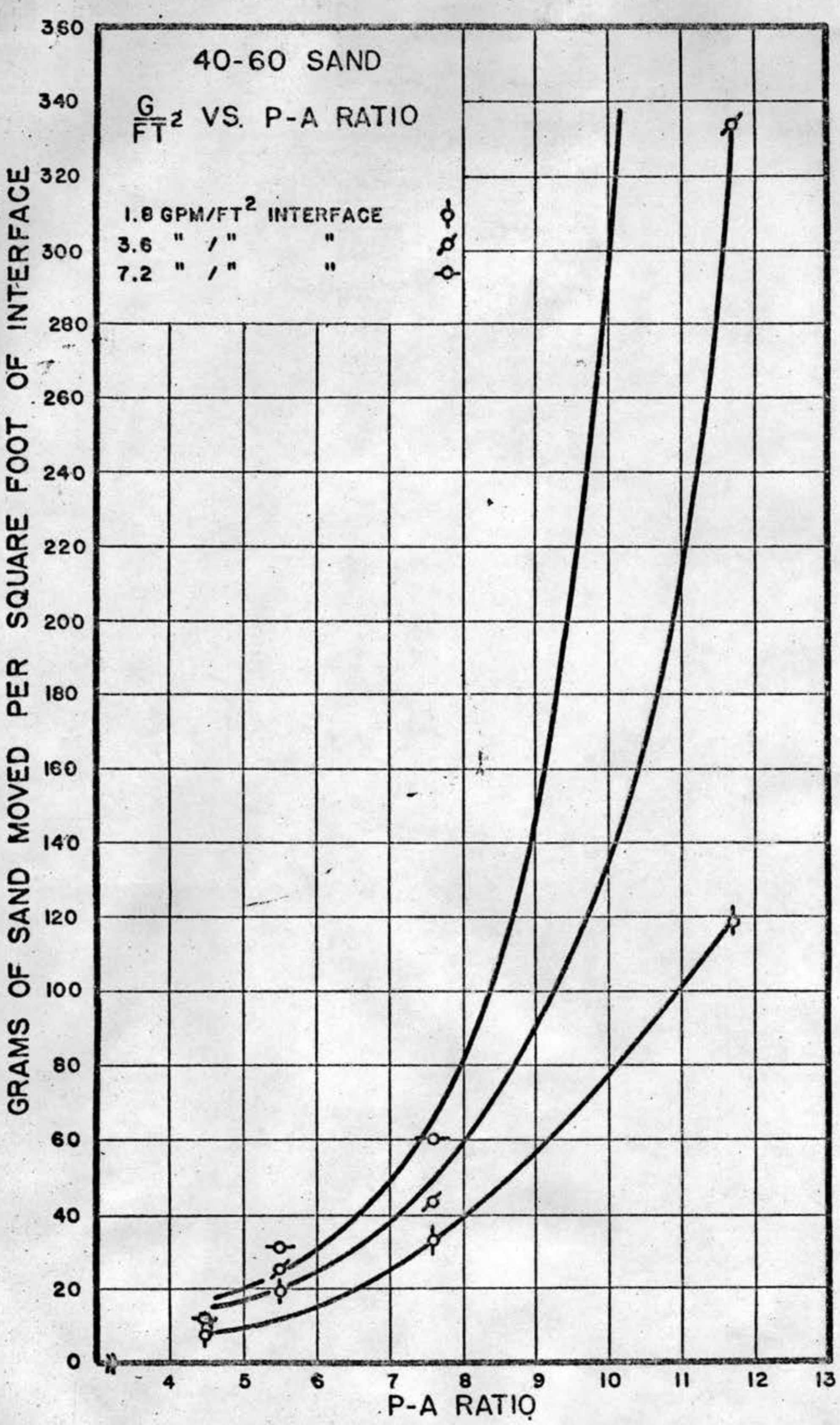


FIG. 18.-Amount of 40-60 sand moved per square foot of interface versus the pack-aquifer ratio at three discharges.

the amount of sand moved increased rapidly with an increase in the P-A ratio. At higher discharges, the amount of sand moved increased rapidly with an increase in the P-A ratio, regardless of the sand used. In the 30-40 and 40-60 sands, the rate of increase in the amount of sand moved increased with an increase in discharge and an increase in the P-A ratio. In the 20-30 sand, the rate of increase in the amount of sand moved remained constant as the P-A ratio increased, except at the highest discharge when the rate of increase in the amount of sand moved increased with an increase in the P-A ratio. Unfortunately, the data for the 20-30 sand, were not considered reliable because of the fine mesh screen used at the sand-gravel interface which interferred with the sand movement into the gravel. This influence became apparent when a coarser screen was used, and was obvious at the highest P-A ratio. With the coarser screen, 6- by 6-mesh, at a P-A ratio of 16.2, the sand moved rapidly into the gravel even before the smallest discharge could be established.

In the 30-40 and 40-60 sands, a point was reached at which the amount of sand moved was nearly constant, regardless of discharge or further reduction of the pack-aquifer ratio. In the 20-30 sand, such a point was never reached because the smallest gravel used with that sand was too coarse to give a P-A ratio sufficiently small, or because of the influence of the interface screen. The point of nearly constant sand movement, within the range of P-A ratios investigated, occurred at a ratio of approximately 3.7 for the 30-40 sand and 4.5 for the 40-60 sand.

The second requirement of an efficient gravel pack is that it must be composed of material whose particle size is as large as possible so that the head loss in the pack will be a minimum and also so that maximum size screen openings may be used. The data, therefore, were analyzed to determine the relationship of the head loss in the gravel pack to the pack-aquifer ratio. Figures 19, 20, and 21 summarize those data.

The head losses at different pack-aquifer ratios and discharges, when sand movement occurred, were obtained from the regular test data. In order to determine the losses in the gravel pack when no sand movement occurred, a series of test runs was made in which no sand was placed in the plastic cylinder. These data are summarized in Table 5. All head losses in the gravel pack were measured between piezometer taps 8 and 15, which were 8.44 inches apart. The comparison of the head losses in the gravel pack with and without sand movement was required to ascertain the effect of the sand movement on the head losses. See Table 6.

At very small pack-aquifer ratios, the head losses were relatively high. As the P-A ratio increased, the head losses in the gravel generally decreased; however, in the 30-40 and 40-60 sands, a P-A ratio was reached above which the head losses either increased again, or decreased more slowly than would have been the case if no sand movement had taken place. In the 20-30 sand, no such P-A ratio was apparent. The point at which the change occurred in the 30-40 and 40-60 sands was at a P-A ratio of approximately 7.5.

From a study of Figures 13, 15, 18, and 21, it was evident that at least one factor other than the pack-aquifer ratio was influencing the amount of sand moved and the head loss in the gravel pack. The only

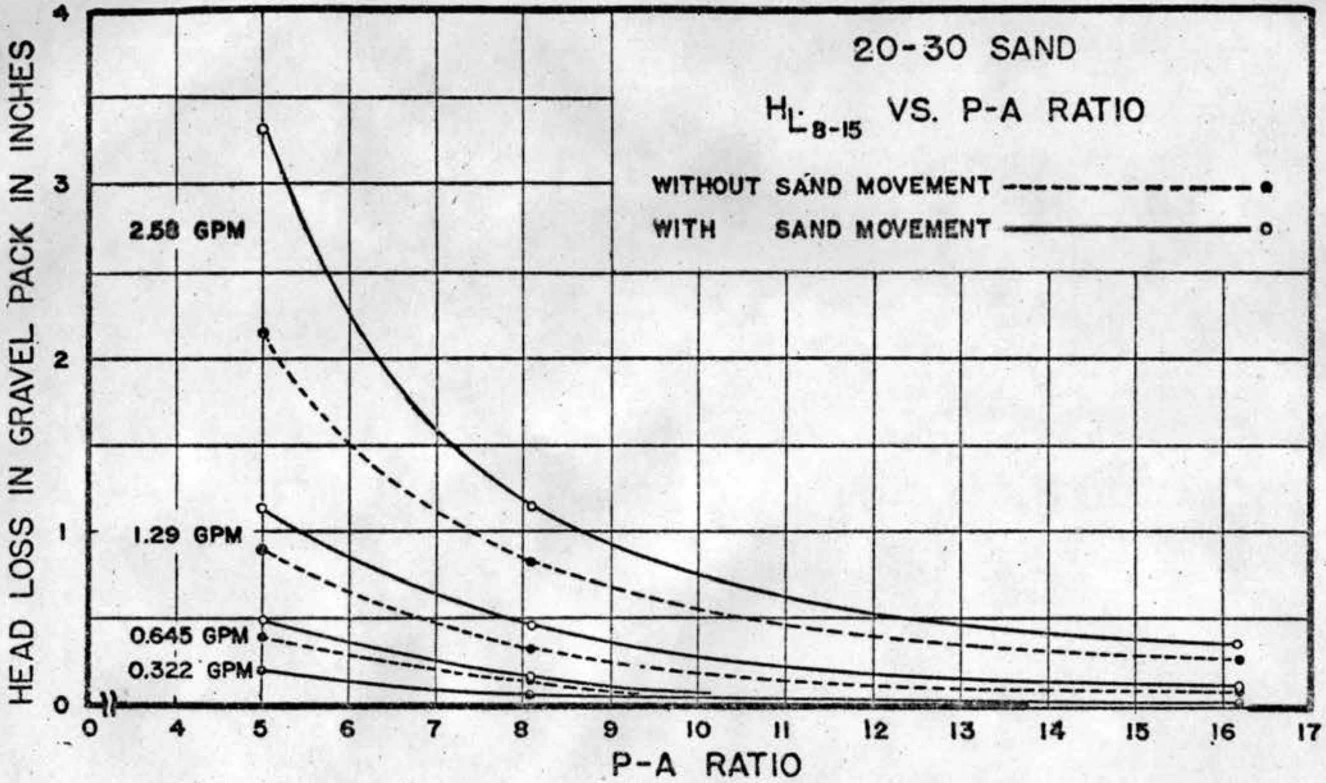


FIG. 19.-Head loss in the gravel pack between taps 8 and 15 versus the pack-aquifer ratio at four discharges with and without sand movement. (Aquifer 20-30 sand).

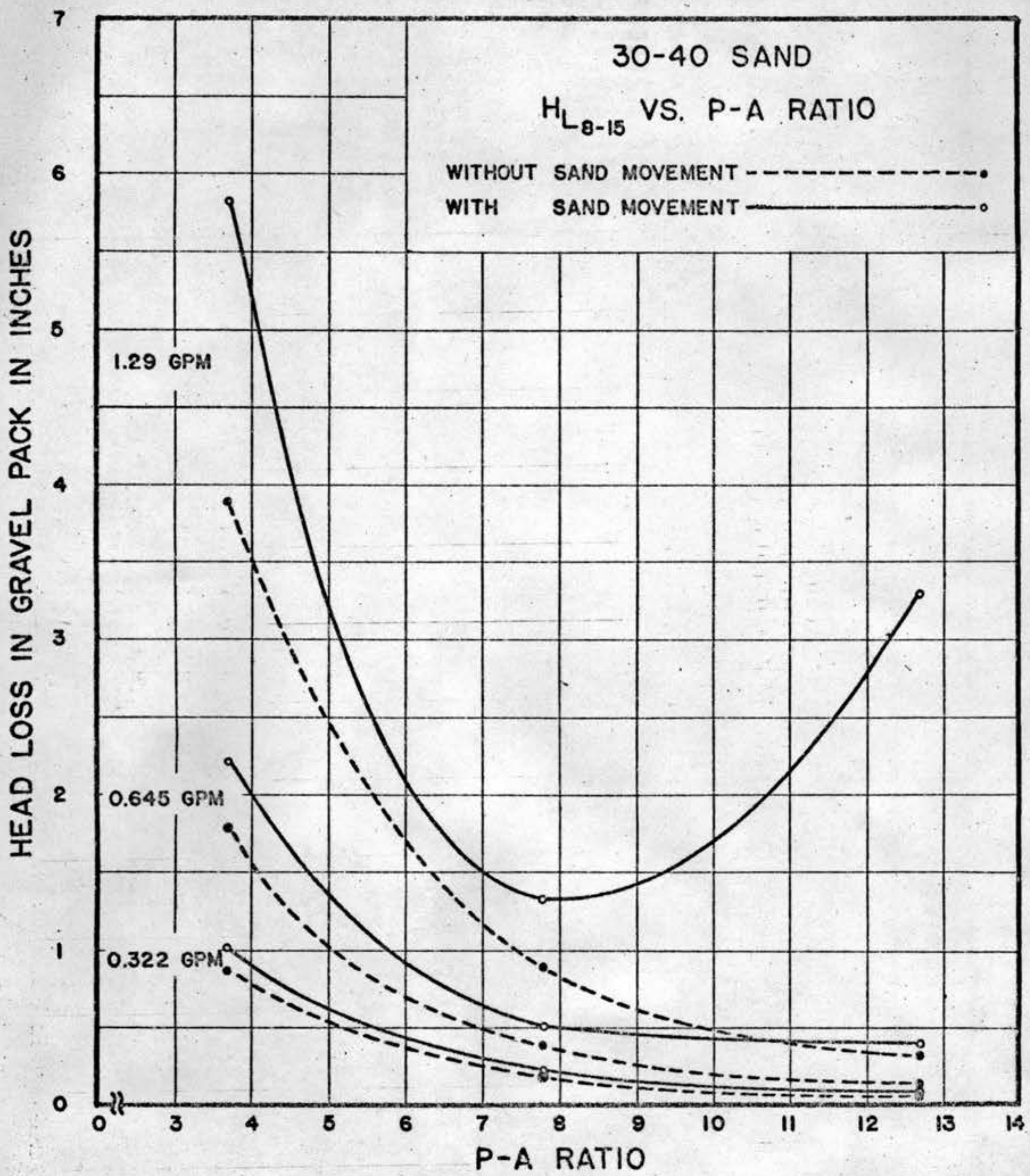


FIG. 20.-Head loss in the gravel pack between taps 8 and 15 versus the pack-aquifer ratio at three discharges, with and without sand movement. (Aquifer 30-40 sand).

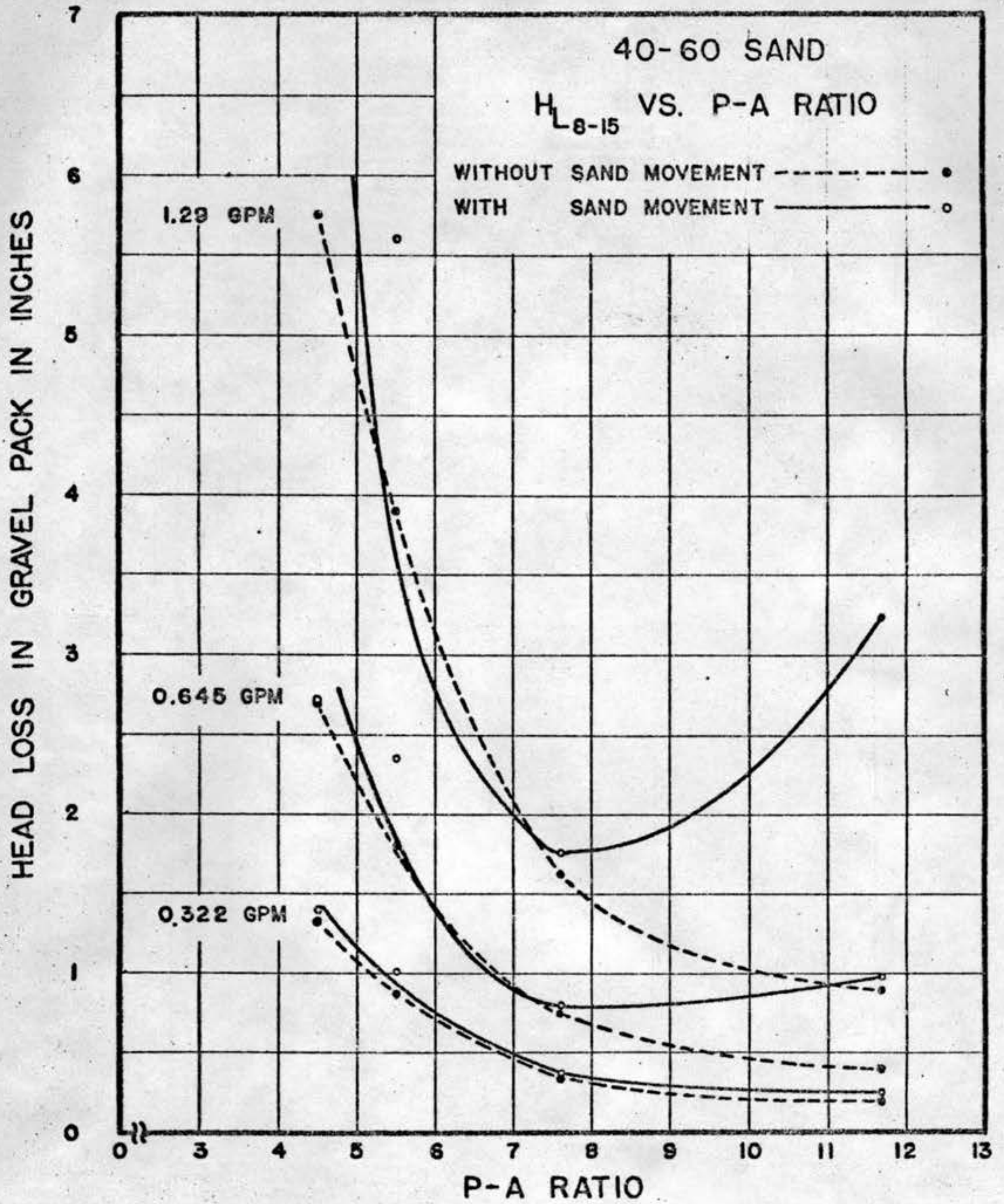


FIG. 21.-Head loss in the gravel pack between taps 8 and 15 versus the pack-aquifer ratio at four discharges, with and without sand movement. (Aquifer 40-60 sand).

Table 5.--HEAD LOSS IN GRAVEL PACK AT DIFFERENT DISCHARGES, WITHOUT SAND IN THE PLASTIC CYLINDER.

Gravel size	Final discharge	Water temperature	Piezometric head at manometer No. 8	Piezometric head at manometer No. 15	Head loss in gravel pack between taps 8 and 15
Inches or U.S. sieve numbers	GPM	Degrees F	Inches	Inches	Inches
	(Q_f)	(t)			$(H_{L_{8-15}})$
1/2-inch	0.325	60	8.16	8.14	0.02
"	0.645	59	14.12	14.08	0.04
"	1.29	59	11.20	11.11	0.09
1/2-inch	2.59	58	17.84	17.57	0.27
1/4-inch	0.355	59	10.52	10.46	0.06
"	0.645	58	14.40	14.27	0.13
"	1.29	58	11.30	10.98	0.32
1/4-inch	2.60	57	18.66	17.83	0.83
1/8-inch	0.335	59	20.70	20.51	0.19
"	0.645	58	14.56	14.17	0.39
"	1.29	58	12.09	11.20	0.89
1/8-inch	2.60	57	19.90	17.75	2.15
8-10	0.325	59	7.31	6.97	0.34
"	0.650	58	15.32	14.58	0.74
"	1.30	57	12.90	11.27	1.63
8-10	2.57	57	21.10	17.24	3.86
1/16-inch	0.325	58	12.29	11.42	0.87
"	0.645	58	16.10	14.31	1.79
"	1.29	58	15.13	11.24	3.89
1/16-inch	2.58	57	26.45	17.52	8.93
14-16	0.320	58	9.24	7.92	1.32
"	0.645	58	16.86	14.18	2.68
"	1.29	57	16.98	11.21	5.77
14-16	2.58	57	30.44	17.62	12.82

Table 6.--HEAD LOSS IN GRAVEL AT DIFFERENT DISCHARGES WITH AND WITHOUT SAND IN THE PLASTIC CYLINDER.

Sand size	Gravel size	P-A ratio	Head loss in gravel pack between taps 8 and 15 at a discharge of			
			Q_f = 0.322 GPM	Q_f = 0.645 GPM	Q_f = 1.29 GPM	Q_f = 2.58 GPM
U.S. sieve numbers	Inches or U.S. sieve numbers		Inches of water	Inches of water	Inches of water	Inches of water
20-30	1/8-inch	5.0	0.21	0.50	1.15	3.32
None	1/8-inch	---	0.19	0.39	0.89	2.15
20-30	1/4-inch	8.1	0.08	0.16	0.46	1.14
None	1/4-inch	---	0.06	0.13	0.32	0.83
20-30	1/2-inch	16.2	0.03	0.03	0.11	0.36
None	1/2-inch	---	0.02	0.04	0.09	0.27
30-40	1/16-inch	3.7	1.02	2.22	5.83	15.72
None	1/16-inch	---	0.87	1.79	3.89	8.93
30-40	1/8-inch	7.8	0.23	0.52	1.34	3.32
None	1/8-inch	---	0.19	0.39	0.89	2.15
30-40	1/4-inch	12.7	0.11	0.41	3.29	---
None	1/4-inch	---	0.06	0.13	0.32	0.83
40-60	14-16	4.5	1.39	2.72	5.75	11.40
None	14-16	---	1.32	2.68	5.77	12.82
40-60	1/16-inch	5.5	1.01	2.35	5.60	---
None	1/16-inch	---	0.87	1.79	3.89	8.93
40-60	8-10	7.6	0.37	0.80	1.76	3.90
None	8-10	---	0.34	0.74	1.63	3.86
40-60	1/8-inch	11.7	0.26	0.98	3.23	---
None	1/8-inch	---	0.19	0.39	0.89	2.15

factors known to be different were the uniformity coefficients of the sands and gravels. The uniformity coefficients of the 14-16, 10-14, and 8-10 gravels were 1.08, 1.16, and 1.10, respectively, or very nearly the same. However, in Figure 18, it appears that more 40-60 sand movement occurred at a P-A ratio of 5.5 with the 10-14 gravel - the gravel with the slightly higher uniformity coefficient - than expected. Figures 13 and 15 also show this, though not so clearly. The uniformity coefficients of the 20-30, 30-40, and 40-60 sands were 1.38, 1.66, and 1.30, respectively. Since the uniformity coefficients of the 20-30 and 40-60 sands were nearly the same, a comparison of the amount of sand moved versus the pack-aquifer ratio of the 20-30 sand with 5-8 gravel (P-A ratio of 5.0) to that of the 40-60 sand with 10-14 gravel (P-A ratio of 5.5) should have shown the same trend. The uniformity coefficient of the 5-8 gravel was 1.32 and of the 10-14 gravel, 1.16, so there was a difference in the gravel uniformity coefficients. Again the combination with the gravel having the smaller uniformity coefficient had the smaller amount of sand moved, even though its P-A ratio was slightly larger. However, since the data involving the 20-30 sand was not considered reliable, the second apparent illustration of the influence of the gravel uniformity had to be discarded. After the discovery of the influence of the fine interface screen used with the 20-30 sand at a high P-A ratio, it was believed that the influence would be negligible at low P-A ratios. A study of Figures 12, 14, and 16, however, made it evident that something, presumably the interface screen, had become a major factor in the amount of sand moved at all P-A ratios. No other comparison involving only the uniformity coefficients of the gravel could be made, and therefore trend could be determined.

In investigating the uniformity coefficient of the aquifer sand, it was evident that this variable was an important factor in the amount of sand moved. In the 30-40 sand with a 10-14 gravel (P-A ratio of 3.7), the amount of sand moved was not a great deal less than the amount moved in a 40-60 sand with a 10-14 gravel (P-A ratio of 5.5). The uniformity coefficient of the gravel could not have been a factor since both gravels were the same. Therefore, the uniformity coefficients of the sands, 1.66 for the 30-40 sand and 1.30 for the 40-60 sands, were compared. The trend indicated was that the smaller the uniformity coefficient of the sand the smaller the amount of sand moved. The same conclusion was reached when the 30-40 sand with 10-14 gravel (P-A ratio of 3.7) was compared to the 40-60 sand with 14-16 gravel (P-A ratio of 4.5). Since the uniformity coefficients of the gravels were nearly the same, 1.16 and 1.08, respectively, it was concluded that it was the smaller uniformity coefficient of the 40-60 sand that accounted for the fact that less 40-60 sand than 30-40 sand moved, even though the P-A ratio of the 40-60 sand with 14-16 gravel was greater than that of the 30-40 sand with 10-14 gravel.

The 30-40 sand with 5-8 gravel (P-A ratio of 7.8) resulted in a great deal of sand movement as shown in Figures 13 and 15. However, the 40-60 sand with 8-10 gravel (P-A ratio of 7.6) resulted in a much smaller amount of sand moved. When the uniformity coefficients were taken into consideration, the large difference in the amount of sand moved in the two cases could be explained. The uniformity coefficients of both the sand and the gravel of the 30-40 sand with 5-8 gravel combination were larger than those of the 40-60 sand with 8-10 gravel combination. Therefore, it could be expected that more of the 30-40 sand would be moved, even though there was little difference in the P-A ratios.

Since the amount of sand moved was apparently influenced by the pack-aquifer ratio and the uniformity coefficient of the sand, an attempt was made to combine both factors into one coefficient. There appeared to be a relationship between the amount of sand moved and the product of the P-A ratio and the uniformity coefficient of the sand. Table 7 summarizes this relationship at one velocity in the sand and one hydraulic gradient as taken from Figures 13 and 15. By comparing Table 7 with Figures 13 and 15, this relationship becomes evident.

The analysis of the data may be summarized as follows:

1- The amount of sand moved varied directly with the velocity of the water through the voids of the sand.

2- The amount of sand moved varied directly with the hydraulic gradient in the sand.

3- For any one sand, the amount of sand moved varied directly with the pack-aquifer ratio.

4- At low pack-aquifer ratios, the rate of increase in the amount of sand moved decreased as the velocity and the hydraulic gradient increased.

5- At high pack-aquifer ratios, the rate of increase in the amount of sand moved increased as the velocity and the

Table 7.--RELATIONSHIP OF THE AMOUNT OF SAND MOVED AT ONE VELOCITY AND ONE HYDRAULIC GRADIENT TO THE PRODUCT OF THE PACK-AQUIFER RATIO AND THE UNIFORMITY COEFFICIENT OF THE AQUIFER SAND.

Sand size	Gravel size	Pack-aquifer ratio (P-A ratio)	Uniformity coefficient of the aquifer sand (C_u aquifer)	(P-A ratio) X (C_u aquifer)	Grams of sand moved	
					At average velocity of 0.03 ft/sec	Per square foot of interface at hydraulic gradient of 5
U.S. sieve numbers	U.S. sieve numbers					
40-60	14-16	4.5	1.30	5.8	1.9	9
30-40	10-14	3.7	1.66	6.1	2.4	11
40-60	10-14	5.5	1.30	7.1	5.2	21
20-30	5-8	5.0	1.38	6.9	5.6	33
40-60	8-10	7.6	1.30	9.9	9.4	40
20-30	3-5	8.1	1.38	11.2	10.1	89
30-40	5-8	7.8	1.66	13.0	15.2	66
40-60	5-8	11.7	1.30	15.2	>100.	167
30-40	3-5	12.7	1.66	21.1	>100.	340

hydraulic gradient increased.

6- For any one sand, the rate of increase in the amount of sand moved increased as the pack-aquifer ratio and the discharge increased.

7- A pack-aquifer ratio was reached below which no further significant reduction in the amount of sand moved occurred, regardless of the discharge. That P-A ratio in the 30-40 sand was 3.7 and in the 40-60 sand was 4.5.

8- The head losses in the gravel pack decreased as the pack-aquifer ratio increased until a point was reached at which the head losses either increased again, or decreased more slowly than would have been the case if no sand movement had taken place. The P-A ratio at which the change occurred was approximately 7.5 for the 30-40 and 40-60 sands.

9- At a given low pack-aquifer ratio, the amount of sand moved varied directly as the uniformity coefficient of the sand.

10- The amount of sand moved varied directly as the product of the pack-aquifer ratio and the uniformity coefficient of the sand.

DISCUSSION

The most important function of a gravel pack is the control of the movement of the sand from the aquifer into the well. It is well understood, that the smaller this amount is, the better the pack is performing this function. Before the data were analyzed, it was thought that even small quantities of sand in the gravel pack would markedly increase the head loss in the pack. The test results showed that it required a considerable amount of sand movement before the head loss in the pack was increased appreciably. This was true because, for a given sand, as the pack-aquifer ratio increased and the amount of sand moved increased, the effect of the increasing gravel size in decreasing head loss was greater than the effect of the sand moved in increasing the head loss. Not until the P-A ratio reached about 7.5 did enough sand move to counteract the influence of greater gravel size. Figures 20 and 21 illustrate this fact.

However, it must be remembered that the test runs were of only 30 minutes duration. It was beyond the scope of this investigation to study the effect of time; however, one test run of 5 hours and 30 minutes was made with a 40-60 sand and an 8-10 gravel (P-A ratio of 7.6) and an initial discharge of 1.27 gpm. At the end of the first hour, the head losses in the sand and gravel were nearly the same as at the beginning of the run, but the discharge had decreased to 1.21 gpm. At the end of the third hour, the discharge was still 1.21 gpm, but the head loss in the gravel had increased 1.0 inch. At the end of the test run of 5 hours and 30 minutes, the discharge had decreased to 1.19 gpm while the head loss in the gravel had increased an additional 2.7 inches. The amount of sand moved was 27.8 grams, or nearly three times the amount moved in the 30 minute runs. This sand-gravel combination was chosen for the longer test run because the data from the regular test runs indicated that a P-A ratio of 7.6 might be near the maximum for reasonable design. Since the uniformity coefficient of the 40-60 sand was 1.30, the product of the P-A ratio and the uniformity coefficient of the aquifer sand was 9.9.

From the data gathered during the test run of 5 hours and 30 minutes, it was apparent that equilibrium had not been established even at the end of this time. The duration of this test was 11 times that of the regular runs, but only three times as much sand moved. No conclusions could be drawn from this single test run; however, with a properly selected pack it would seem reasonable to desire less sand movement. As a result, the upper limit of the product of the pack-aquifer ratio and the uniformity coefficient of the aquifer sand would have to be less than 9.9.

It must also be remembered that in the plastic cylinder used, the flow lines were parallel and not radial as they would be in a well. As a result of the parallel flow lines, practically no sand was carried through the pack into the well section of the cylinder. With radial flow, the driving force would have tended to move the sand farther into and through the pack, because of increasing velocity and hydraulic gradient.

For each of the three sands tested, the amount of sand moved varied directly with the velocity of the water, the hydraulic gradient, and the pack-aquifer ratio, as expected. Of particular importance, however, was the fact that at low P-A ratios the rate of increase in the amount of sand moved decreased as the velocity and the hydraulic gradient increased. The gravel pack, therefore, should be selected so that doubling the discharge of the well will result in only a small increase in the amount of sand moved. This criterion would serve as a safety factor to prevent permanent damage to a well if overpumped accidently for a short period of time. Sand once in the gravel pack, unless able to move entirely through into the well, permanently exerts its harmful effects upon the well. Figures 13 and 15, illustrate this point. The sand-gravel combinations for the three lowermost curves in the figures would meet the criterion; the sand-gravel combinations of the next two curves, lying just above the lower three, would be questionable; and the sand-gravel combinations of the four uppermost curves would definitely be rejected.

The influence of the uniformity coefficient of the sand upon the amount of sand moved was clearly evident from the analysis of the data. It seemed reasonable to expect that the pack-aquifer ratio at stability would be the same for all sands, if all other factors were identical. Stability denotes the condition when no sand movement can occur. In the 30-40 and 40-60 sands tested, the P-A ratio at which each reached stability was 3.7 and 4.5, respectively. The uniformity coefficient C_u of the 30-40 and 40-60 sands were 1.66 and 1.30, respectively. In other words, the 30-40 sand had a higher percentage of fines than the 40-60 sand. In order to prevent movement of the fines, the gravel had to be finer, and the result was a smaller P-A ratio. However, when the uniformity coefficients were taken into consideration, the products obtained by multiplying the P-A ratio and the uniformity coefficient of the sand were nearly the same for both sands. They were 6.1 and 5.8 for the 30-40 and 40-60 sands, respectively. A value of 6.0, therefore, was selected as the approximate maximum value of $\left[(\text{P-A ratio}) \times (C_u \text{ aquifer})\right]$ at which stable conditions could be expected.

Bennison (3) suggested that a well in an aquifer sand with a uniformity coefficient greater than 2.0 need not be gravel packed. His main reason for suggesting this number was that an aquifer sand with a higher coefficient could be developed so as to produce its own gravel pack "naturally". It is evident from this study that the greater the uniformity coefficient of the aquifer sand, the finer the gravel in the pack must be in order to be satisfactory. Since many well drillers are convinced that the gravel in the pack must be coarse, it is very understandable why so many of them get into trouble, particularly when they attempt to gravel-pack wells in aquifers with high uniformity coefficients. The coarse gravel has such large voids that the finer aquifer particles are carried into the pack or through the pack into the well. The result is either a clogged gravel pack or a sand-producing well. No part of this study was concerned with the development of "natural" gravel packs; the results, however, tend to corroborate the recommendation of Bennison.

Smith (32) reported that a well in which the uniformity coefficient of the aquifer and pack were 8.3 and 1.5, respectively, (P-A ratio of 5.1) produced no sand. The resulting product of the P-A ratio and the uniformity coefficient of the aquifer is 42.3. This would seem to contradict the findings of this study; however, Smith did not report the discharge and other data necessary to determine the water velocity or hydraulic gradient at the interface. The discharge per unit of pack-aquifer interface, which is related to the velocity and hydraulic gradient in the aquifer, has an important influence on the amount of sand moved, except where complete stability occurs. No comparison between the report of Smith and this study, therefore, can be made.

Insufficient appropriate data prevented a study of the influence of the uniformity of the gravel in the pack upon the amount of sand moved. In the 40-60 sand, the only sand in which a sufficient number of sand-gravel combinations was tested to have shown any trend, the uniformity coefficients of the gravel were so nearly the same that no significant effect could be produced. In figure 18, the position of the series of points at the pack-aquifer ratio of 5.5 (40-60 sand with 10-14 gravel) does not conform closely to the pattern of positions of the series of points at P-A ratios of 4.5 and 7.6. The uniformity coefficient of the sand could not have been responsible since all three combinations had the same sand. To conclude that the very slight difference in the uniformity coefficient of the gravel was responsible was not warranted without further evidence. It may have been merely the result of a normal range in the data because of the experimental method; however, the amount of sand moved was more than expected where the uniformity coefficient of the gravel was highest.

Other investigators have shown the desirability of using uniform gravels to insure voids of maximum size and to prevent compaction. Uniform gravels in the pack, therefore, aid in the reduction of pack head losses. The influence of the uniformity coefficient of the gravel on the pack head losses is not evident in this study because all of the gravels used were uniform. The maximum uniformity coefficient of the tested gravels was 1.32. It is suggested that the uniformity coefficient of the gravel for a pack be 2.0 or less.

Following is a listing of the criteria established by others for the selection of gravel for filter or pack.

Terzaghi, $\frac{D_{15}\text{ filter}}{D_{85}\text{ soil}} \leq 4 \leq \frac{D_{15}\text{ filter}}{D_{15}\text{ soil}}$

Bertram, $\frac{D_{15}\text{ filter}}{D_{85}\text{ soil}} = 8\text{ to }10$

U. S. Waterways Experiment Station, $\frac{D_{15}\text{ filter}}{D_{85}\text{ base}} \leq (4\text{ to }5) \leq \frac{D_{15}\text{ filter}}{D_{15}\text{ base}}$

U. S. Bureau of Reclamation, $\frac{D_{50}\text{ filter}}{D_{50}\text{ base}} = 5\text{ to }10$

Leatherwood, $\frac{D_{15}\text{ gravel}}{D_{85}\text{ sand}} < 4.1$; $\frac{D_{50}\text{ gravel}}{D_{50}\text{ sand}} < 5.3$

Smith, $\frac{D_{50}\text{ pack}}{D_{50}\text{ sand}} = 4\text{ to }6$

Bennison, $\frac{D_{10}\text{ pack}}{D_{10}\text{ sand}} =$ (value unpublished)

For comparative purposes, the terms filter, gravel, and pack may be considered synonymous. Also, the terms soil, base, sand, and aquifer may be considered synonymous.

Table 8 lists the ratios of various percentage sizes and uniformity coefficients of pack to aquifer and also the product of the pack-aquifer ratio and the uniformity coefficient of the aquifer sand, $\left[(\text{P-A ratio}) \times (C_u \text{ aquifer})\right]$, determined in this study.

The criteria established by Bertram (6) and the U. S. Bureau of Reclamation (39) are not comparable with the others because both used compacted samples. The values obtained by them are, as a result, much higher than those obtained in this study and by the other investigators.

The different percentage sizes upon which the investigators have based their criteria are numerous. Table 8 includes all of the ratios indicated above for ease in comparison. In the 30-40 sand tested in this investigation, stability was achieved when the values for the ratios of the various percentage sizes were as follows:

$$(\text{P-A ratio}) = \frac{D_{50}\text{ pack}}{D_{50}\text{ sand}} = 3.7\ ;\ \frac{D_{15}\text{ pack}}{D_{15}\text{ sand}} = 4.9\ ;\ \frac{D_{15}\text{ pack}}{D_{85}\text{ sand}} = 2.7\ ;$$

$$\text{and } \frac{D_{10}\text{ pack}}{D_{10}\text{ sand}} = 5.0\ .$$

In the 40-60 sand tested, stability was achieved when the values for the ratios of the various percentage sizes were as follows:

$$(\text{P-A ratio}) = \frac{D_{50}\text{ pack}}{D_{50}\text{ sand}} = 4.5\ ;\ \frac{D_{15}\text{ pack}}{D_{15}\text{ sand}} = 5.1\ ;\ \frac{D_{15}\text{ pack}}{D_{85}\text{ sand}} = 3.5\ ;$$

$$\text{and } \frac{D_{10}\text{ pack}}{D_{10}\text{ sand}} = 5.3\ .$$

Table 8.--RATIOS OF SELECTED PERCENTAGE SIZES OF THE GRAVEL PACK TO THE AQUIFER, AND THE PRODUCTS OF THE PACK-AQUIFER RATIO AND THE UNIFORMITY COEFFICIENT OF THE AQUIFER FOR COMPARISON OF DESIGN CRITERIA.

Pack / Aquifer (U.S. sieve numbers)	D_{50} Pack / D_{50} Aquifer (P-A Ratio)	D_{15} Pack / D_{15} Aquifer	D_{15} Pack / D_{85} Aquifer	D_{10} Pack / D_{10} Aquifer	(P-A Ratio) x (C_u Aquifer)
20-30 / 40-60	2.3	2.3	1.5	2.3	3.0
14-16 / 40-60	4.5	5.1	3.5	5.3	5.8
10-14 / 40-60	5.5	6.1	4.2	6.1	7.2
8-10 / 40-60	7.6	8.6	5.9	8.8	9.9
5-8 / 40-60	11.7	11.4	7.8	11.3	15.2
14-16 / 30-40	3.0	4.1	2.3	4.4	5.0
10-14 / 30-40	3.7	4.9	2.7	5.0	6.1
8-10 / 30-40	5.1	6.9	3.8	7.2	8.5
5-8 / 30-40	7.8	9.1	5.1	9.3	13.0
3-5 / 30-40	12.7	16.5	9.2	17.3	21.1
8-10 / 20-30	3.2	3.8	2.6	3.9	4.4
5-8 / 20-30	5.0	5.1	3.5	5.0	6.9
3-5 / 20-30	8.1	9.2	6.3	9.3	11.2

In both the 30-40 and 40-60 sands, the results agree with those of Terzaghi and the U. S. Waterways Experiment Station. The values determined by Leatherwood are higher than those obtained in this study, slightly higher than those of Terzaghi, and within the limits as determined by the U. S. Waterways Experiment Station. The higher values suggested by Leatherwood may have resulted from his method of determining stability.

Apparently, neither Terzaghi nor the U. S. Waterways Experiment Station found any important relationship between the uniformity coefficient of the gravel and stability, for their criteria based on the ratios of the 15-percent size of the filter to the 15- and 85-percent sizes of the base material do not control, in any way, the uniformity coefficient of the filter material. In order to include such a provision in their criteria, the 85-percent size, or some other high percent size, of the gravel would have to be included. The uniformity coefficient of the sand is controlled by the criteria.

The criteria suggested by Leatherwood, (16) since it included both the 15- and the 50-percent sizes of the gravel, would affect the uniformity coefficient of the gravel. However, nothing in the criteria controls the percentage of fines in the sand. The uniformity coefficient of the sand, therefore, is not influenced by the criteria.

Leatherwood, Smith, and Bennison were concerned only with uniform gravels. Leatherwood and Bennison further restricted their criteria to uniform sands. Smith extended his criterion to include non-uniform sands, as discussed elsewhere in this chapter. Apparently, they concluded that the restrictions placed upon the use of their criteria provided for the uniformity factors not expressly specified. The results of this study, however, have shown that the uniformity coefficient of the sand, even in uniform sands, was an important factor. Terzaghi and the U. S. Waterways Experiment Station were primarily concerned with criteria for use with base materials having high uniformity coefficients, and therefore, had to make provision for that factor.

Throughout this study, it has been implied that the grain-size distribution of the aquifer sand must be known before a gravel pack can be selected. In actual practice, the need for a gravel pack is not known until an accurate knowledge of the aquifer is gained. The well contractor must know how to obtain accurate, representative samples of the aquifer. This is not a simple task without special equipment. Once the samples are taken there is not time to submit them to a laboratory miles away for analysis. They must be dried, sieved, and analyzed at the well site. This can be done without expensive equipment in a short time, yet it rarely is done at present.

For practical design purposes, a reasonable range must be provided in the criteria so that the resulting gravel pack operates efficiently and still permits the contractor to comply. Based on the results of the laboratory study, the following design criteria are suggested:

(a) The gravel should be selected so that the product of the pack-aquifer ratio and the uniformity coefficient of the aquifer sand is from 5.0 to 8.0.

$$(\text{P-A ratio}) \times (C_u \text{ aquifer}) = (5.0 \text{ to } 8.0)$$

(b) Only aquifer sands with uniformity coefficients of 2.0 or less should be gravel packed.

$(C_u \text{ aquifer}) = 2.0$

The minimum value of 5.0, under (a) above, is suggested because any smaller value would result in higher head loss through the pack without any appreciable reduction in the amount of sand moved. The maximum value of 6.0, under (a) above, is suggested because any greater value would result in an appreciable increase in the amount of sand moved with increase in discharge.

In criterion (b) above, the maximum value of 2.0 for the uniformity coefficient of the aquifer is suggested because any larger value results in gravel approaching in size that of the aquifer sand. Excessive head losses in the pack and through the smaller screen openings make the gravel packing of sands with higher uniformity coefficients uneconomical, and probably unnecessary.

SUGGESTIONS FOR FURTHER STUDY

Many factors of possible importance in the selection of gravel packs were beyond the scope of this study. Other factors of importance became evident during the test runs or while analyzing the data. Therefore, the following suggestions for further study are made:

1- What is the effect of time on the amount of sand moved, on the head loss in the gravel pack, and on the criteria for stability?

2- What is the effect of changing the thickness of the gravel pack on the amount of sand moved and on the criteria for stability?

3- What is the effect of the percentage of open area in the well screen on the amount of sand moved with gravel packs of different thickness?

4- What is the effect of the size of slot in the well screen on the amount of sand moved with gravel packs of different thickness?

5- Is the uniformity coefficient of the gravel an important factor in design criteria?

6- Is the maximum value of 2.0 for the uniformity coefficients of the sand and gravel justified, or what should be the criteria for determining when an aquifer should be gravel packed?

7- The laboratory work of this study should be continued so as to include sand-gravel combinations with pack-aquifer ratios which would supplement the data of this study. The effect of the uniformity coefficients of both the sands and the gravels should also be studied.

Since the uniformity of the aquifer seems to have the greatest effect on the amount of sand moved, the effect of this factor should be investigated first.

SUMMARY

If properly selected, the gravel pack prevents any sand from entering the well that might damage the pumping equipment, and makes it possible to get the maximum amount of water at a given pumping lift, or a given amount of water at a minimum pumping lift. Unfortunately, many gravel-packed wells have caused endless trouble and disappointment because the proper gravel pack was not used.

Only a limited amount of study has been devoted to gravel pack criteria for wells. The number of published reports of such studies is small. This study is an attempt to add something to the meager amount of available information concerning this important aspect of ground water development.

In order to investigate the relationship between the aquifer sand and the gravel pack so that criteria for the selection of gravel can be made, equipment was constructed which permitted the testing of different sand-gravel combinations. The test apparatus and the test procedure were designed so that measurements of discharge, piezometric heads in both the sand and the gravel, the amount of sand moved, and the water temperature could be made. Only uniform sands and gravels were used in the testing program. The maximum uniformity coefficients were 1.66 for the aquifer sands and 1.32 for the pack gravels.

The control of the movement of the aquifer sand is the most important function that a gravel pack must perform. Therefore, the relationships of the amount of sand moved to several factors were studied. These

factors were as follows: (a) the velocity of the water through the sand voids; (b) the hydraulic gradient in the sand; (c) the ratio of the 50-percent sizes of the gravel to the sand, called the pack-aquifer ratio (P-A ratio) in this study; and (d) the uniformity coefficients of the gravel and sand.

The second function which a properly selected gravel pack performs is to insure minimum head loss in the pack itself, and also minimum entrance loss at the well by permitting the use of maximum size slots in the well screen. Therefore, the relationship of the amount of sand moved to the head loss in the gravel pack was studied.

Stability of the sand, i.e., when no sand movement took place, occurred when the product of the pack-aquifer ratio and the uniformity coefficient of the aquifer sand was approximately 6.0 or less. The rate of increase in the amount of sand moved was very small until the product of these two factors reached approximately 8.0.

The head loss in the gravel pack was not appreciably affected by the movement of the sand at the end of a 30 minute test run, at pack-aquifer ratios less than approximately 7.5. As the P-A ratio increased from a small value to 7.5, the effect of the increasing gravel size in decreasing the head loss was greater than the effect of the sand moved in increasing the head loss. However, at larger values of the P-A ratio, the head loss either again increased, or decreased at a slower rate than if no sand had moved.

The results of this study show that two factors must be considered if a successful gravel pack is to be selected. The two factors are:

(a) the pack-aquifer particle size relationship, as measured by the pack-aquifer ratio; and (b) the uniformity of the aquifer sand as measured by the uniformity coefficient of the sand.

The criteria suggested by this study for the selection of efficient gravel packs are as follows:

(a) The gravel should be selected so that the product of the pack-aquifer ratio and the uniformity coefficient of the aquifer sand is from 5.0 to 8.0.

$$(\text{P-A ratio}) \times (C_u \text{ aquifer}) = (5.0 \text{ to } 8.0)$$

(b) Only aquifer sands with uniformity coefficients of 2.0 or less should be gravel packed.

$$(C_u \text{ aquifer}) \leq 2.0$$

Although not a result of this study, it is further suggested that the uniformity coefficient of the gravel should not exceed 2.0.

$$(C_u \text{ pack}) \leq 2.0$$

These conclusions are based on laboratory studies of a rather limited range of sands. Further study of the flow of sand into wells, particularly for sands with higher uniformity coefficients may make it necessary to change the constants in the recommended criteria.

DEFINITIONS

Aquifer: Water bearing formation.

Gravel pack, gravel envelope: Selected gravel layer placed around well screen.

Pack-aquifer ratio: Ratio of 50-percent size of gravel pack to 50-percent size of aquifer. The 50-percent size is that size which has 50 percent by weight smaller than it is and 50 percent larger. Other percentage sizes such as 10, 15, 60 and 85, refer to the sizes that have the designated percentages by weight smaller than they are.

Uniformity coefficient: The ratio of the 60-percent size of the material to the 10-percent size.

ACKNOWLEDGMENTS

The authors are grateful to Dr. D. F. Peterson, W. E. Code and Norman Evans of the Civil Engineering Department of Colorado A and M College and to Dr. Robert S. Whitney of the Agronomy Department for their help in planning the study and interpreting the data; to A. R. Robinson of the Agricultural Research Service, U.S.D.A., who made a careful review of the report; and to Ralph Asmus for his help in designing some of the equipment for the tests.

BIBLIOGRAPHY

1. Bakhmeteff, B. A. and Feodoroff, N. V. Flow through granular media. American Society of Mechanical Engineers. Transactions, 59:A-97-A-104, 1937.

2. Bennison, E. W. Construction and use of well screens. American Water Works Association. Journal, 31:939-50, June 1939.

3. Bennison, E. W. Ground Water. St. Paul, Edward E. Johnson, Inc., 1947. 509 p.

4. Bennison, E. W. Importance of development work in well construction. American Water Works Association. Journal, 41:62-6, January 1949.

5. Bennison, E. W. and others. Useful life of water wells. American Water Works Association. Journal, 39:32-40, January 1947.

6. Bertram, C. E. An experimental investigation of protective filters. Harvard University. Soil Mechanics Series, 7:1-21, 1940.

7. Corey, G. L. Hydraulic properties of well screens. Master's Thesis, 1949. Colorado A & M College. 84 p. ms.

8. Davis, C. V. Handbook of applied hydraulics. New York, McGraw-Hill Book Company, 1952. 1272 p.

9. Franzini, Joseph B. Porosity factor for case of laminar flow through granular media. American Geophysical Union. Transactions, 32:443-6, June 1951.

10. Hansen, V. E. Unconfined ground-water flow to multiple wells. American Society of Civil Engineers. Proceedings, Volume 78, Separate No. 142:1-18, August 1952.

BIBLIOGRAPHY.--Continued

11. Johnston, G. N. Irrigation wells and well drilling. California. Agricultural Experiment Station. Circular 404:1-32, May 1951.

12. Israelsen, O. W., Peterson, D. F. Jr., and Reeve, R. C. Effectiveness of gravity drains and experimental pumping for drainage. Utah. Agricultural Experiment Station. Bulletin, 345:1-64, 1951.

13. Jacob, C. E. Notes on Darcy's law and permeability. American Geophysical Union. Transactions, 27: 265-278, 1946.

14. King, H. W. Handbook of hydraulics. New York, McGraw-Hill Book Company, 1939. 617 p.

15. Lane, E. W. Progress report on studies on the design of stable channels by the Bureau of Reclamation. American Society of Civil Engineers. Proceedings, Volume 79, Separate No. 280:1-31, September 1953.

16. Leatherwood, F. N. Hydraulic head loss at the interface between porous media of different sizes. Master's Thesis, 1952. Colorado A & M College. 98 p. ms.

17. Luthin, J. H. and Scott, V. H. Numerical analysis of flow through aquifers toward wells. Agricultural Engineering, 33:279-82, May 1952.

18. McManamna, T. L. Location and development of gravel-wall wells. Water and Sewage, 83:48-9, April 1945.

19. Meeks, T. O. Developing and testing irrigation wells. U. S. Department of Agriculture. Soil Conservation Service. Region 6, Regional bulletin 114:1-44, March 1952. mimeographed.

20. Meinzer, O. E. (Editor) Hydrology. New York, Dover Publications, 1949. 712 p.

BIBLIOGRAPHY.--Continued

21. Meinzer, O. E. Outline of ground-water hydrology, with definitions. Washington, U. S. Geological Survey. Water supply paper no. 494:1-71, 1923.

22. Meinzer, O. E. Outline of methods for estimating ground-water supplies. U. S. Geological Survey, Water supply paper no. 638-C:99-144, 1932.

23. Millis, J. B. Guide charts in development of ground-water supplies. Oil and Gas Journal, 48:122, August 25, 1949.

24. Murphy, J. B. For low-cost, dependable water. Power, 95:74-6, August 1951.

25. Muskat, M. Flow of homogeneous fluids through porous media. New York, McGraw-Hill Book Company, 1937. 763 p.

26. Peterson, D. F. Jr., Israelsen, O. W., Hansen, V. E. Hydraulics of wells. Utah. Agricultural Experiment Station, Bulletin 351:1-48, March 1952.

27. Petersen, J. S. Effect of well screens on flow into wells. Master's Thesis, 1951. Colorado A & M College. 110 p. ms.

28. Rohwer, Carl. The hydraulics of water wells. Logan, Utah, U. S. Soil Conservation Service, Division of Irrigation, 1947. 15 p. mimeographed.

29. Rohwer, Carl. Putting down and developing wells for irrigation. U. S. Department of Agriculture. Circular, no. 546:1-87, 1940.

30. Rouse, Hunter. Elementary mechanics of fluids. New York, John Wiley & Sons, 1946. 376 p.

31. Shallow wells tap Dismal Swamp for city water supply. Engineering News Record, 133:644-8, November 16, 1944.

32. Smith, Harman F. Gravel packing water wells. Water Well Journal, 8:15-17, January/February 1954.

BIBLIOGRAPHY.--Continued

33. Standard specifications for deep wells. New York, American Water Works Association, June 1951. 47 p.

34. Steel, E. W. Water supply and sewerage. New York, McGraw-Hill Book Company, 1947. 666 p.

35. Symons, G. E. Water works practices; source of supply, location, and construction of wells. Water and Sewage Works, 101:23-7, January 1954.

36. Taylor, D. W. Fundamentals of soil mechanics. New York, John Wiley and Sons, 1948. 700 p.

37. Terzaghi, Karl and Peck, R. B. Soil mechanics in engineering practice. New York, John Wiley & Sons, 1948. 566 p.

38. Tolman, C. F. Ground water. New York, McGraw-Hill Book Company, 1937. 593 p.

39. U. S. Bureau of Reclamation. Laboratory tests on protective filters for hydraulic and static structures. Denver, Colorado, 1947. 28 p. (Earth Material Laboratory report no. EM-132.)

40. U. S. Waterways Experiment Station. Field and laboratory investigations of design criteria for drainage wells. Vicksburg, Mississippi, 1942. 78 p. (Technical memorandum no. 195-1.)

41. U. S. Waterways Experiment Station. Investigation of filter requirements for underdrains. Vicksburg, Mississippi, 1941. 35 p. (Technical memorandum no. 183-1.)

42. Useful life of water wells. Engineering News Record, 136:847-8, May 30, 1946.

43. Wenzel, L. K. Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods. U. S. Geological Survey, Water supply paper no. 887:1-192, 1942.

BIBLIOGRAPHY.--Continued

44. White, H. L. Gravel-packed wells. American Water Works Association. Journal, 29:475-83, April 1937.

45. Wisler, C. O. and Brater, E. F. Hydrology. New York, John Wiley & Sons, 1949. 419 p.

Table 1.--SUMMARY OF RESULTS OF TESTS TO DETERMINE THE FLOW OF SAND AND THE LOSS OF HEAD, AT VARIOUS DISCHARGE RATES FOR DIFFERENT PACK-AQUIFER RATIOS, WHEN USED WITH WELL SCREENS OF DIVERSE TYPES AND DIFFERENT SCREEN OPENINGS.

Test no.	Sand size	Gravel size	Pack-aquifer ratio	Discharge: Initial	Discharge: Final	Discharge: Average	Amount of sand moved	Interface screen	Well screen: Type	Well screen: Slot opening	Water temperature	Piezometric head in inches of water in manometers at final discharge: No. 3	No. 5	No. 8	No. 13	No. 15
	U. S. sieve numbers	Inches or sieve numbers		GPM	GPM	GPM	Grams	Mesh per inch		Inch	Degree F					
				(Q_i)	(Q_f)	(Q_a)	(G)				(t)					
1	20-30	½-inch	16.2	0.325	0.325	0.325	5.6	10x10	B	3/16	57	21.57	17.28	16.57	16.56	16.55
2	"	"	"	0.650	0.640	0.645	7.0	"	"	"	56	27.77	16.68	14.57	14.55	14.52
3	"	"	"	1.30	1.26	1.28	45.9	"	"	"	54	38.71	15.13	9.87	9.85	9.76
4	"	"	"	2.48	2.70	2.59	38.1	"	"	"	50	70.0	31.12	21.35	21.23	20.97
5	"	"	"	0.315	0.315	0.315	3.5	"	C	0.200	53	13.01	8.53	7.83	7.82	7.81
6	"	"	"	0.640	0.630	0.635	6.3	"	"	"	53	25.33	15.25	12.74	12.72	12.69
7	"	"	"	1.31	1.27	1.29	28.7	"	"	"	53	39.64	15.87	10.35	10.28	10.22
8	"	"	"	2.48	2.70	2.59	92.8	"	"	"	52	66.80	29.22	20.70	20.57	20.35
9	"	"	"	0.325	0.325	0.325	3.8	"	D	3/16	52	11.30	7.22	6.46	6.44	6.42
10	"	"	"	0.645	0.635	0.640	3.5	"	"	"	51	25.39	15.50	13.63	13.62	[illegible].62
11	"	"	"	1.30	1.27	1.28	27.6	"	"	"	53	37.53	14.90	10.06	10.03	[illegible].98
12	"	"	"	2.54	2.76	2.65	126.5	"	"	"	51	64.5	27.30	22.28	22.15	[illegible].89
135	20-30	½-inch	16.2	0.322	---	---	Wash out	6x6	B	3/16	---	---	---	---	---	
13	20-30	¼-inch	8.1	0.325	0.320	0.322	2.6	10x10	B	3/16	56	7.02	3.03	2.17	2.14	[illegible].11
14	"	"	"	0.655	0.640	0.648	4.6	"	"	"	52	28.29	16.82	14.28	14.24	[illegible].13
15	"	"	"	1.29	1.29	1.29	14.9	"	"	"	47	44.27	17.76	11.30	11.06	10.77
16	"	"	"	2.50	2.66	2.58	12.9	"	"	"	46	70.8	32.62	20.41	20.12	19.31
17	"	"	"	0.325	0.325	0.325	2.9	"	C	0.100	52	13.15	8.58	7.66	7.64	7.60
18	"	"	"	0.645	0.640	0.642	3.2	"	"	"	50	27.91	16.29	13.72	13.67	13.57
19	"	"	"	1.30	1.27	1.28	13.9	"	"	"	48	43.85	16.77	10.58	10.41	10.12
20	"	"	"	2.46	2.62	2.54	35.1	"	"	"	48	72.4	29.44	19.55	19.00	18.32
21	"	"	"	0.325	0.325	0.325	3.5	"	D	3/16	50	6.78	1.66	0.89	0.87	0.84
22	"	"	"	0.660	0.645	0.652	3.8	"	"	"	49	29.37	16.41	14.22	14.16	14.05
23	"	"	"	1.30	1.26	1.28	13.1	"	"	"	48	45.88	16.57	10.46	10.36	10.08
24	"	"	"	2.50	2.66	2.58	32.2	"	"	"	48	75.	28.17	20.60	20.02	19.27
133	"	"	"	2.49	2.56	2.52	31.3	6x6	B	3/16	48	43.61	23.77	18.11	17.82	17.26
134	20-30	¼-inch	8.1	5.04	5.26	5.15	88.6	6x6	B	3/16	48	85.	45.90	39.41	37.76	36.22
25	20-30	1/8-inch	5.0	0.325	0.320	0.322	2.0	10x10	B	1/8	48	11.66	6.83	5.87	5.82	5.66
26	"	"	"	0.645	0.635	0.640	1.8	"	"	"	45	28.68	17.00	14.16	14.01	13.61
27	"	"	"	1.31	1.26	1.28	5.7	"	"	"	48	46.10	18.58	11.13	10.79	9.98
28	"	"	"	2.39	2.67	2.53	8.3	"	"	"	46	81.	36.18	23.32	21.97	19.74
29	"	"	"	0.320	0.315	0.318	2.6	"	C	0.040	51	6.15	1.47	0.20	0.15	0.00
30	"	"	"	0.650	0.645	0.648	6.6	"	"	"	48	30.50	17.12	14.26	14.12	13.72
31	"	"	"	1.31	1.27	1.29	7.1	"	"	"	47	48.00	18.70	11.29	10.97	10.18
32	"	"	"	2.51	2.72	2.62	7.5	"	"	"	42	77.5	37.43	24.00	22.88	20.73
33	"	"	"	0.325	0.320	0.322	3.3	"	D	1/8	51	26.54	22.58	21.96	21.90	21.75
34	"	"	"	0.660	0.645	0.652	2.7	"	"	"	47	28.85	16.73	14.89	14.76	14.41
35	"	"	"	1.32	1.29	1.30	5.2	"	"	"	45	44.47	17.80	12.46	12.12	11.27
36	"	"	"	2.49	2.61	2.55	8.6	"	"	"	44	70.7	31.67	21.54	20.44	18.44
131	"	"	"	0.655	0.655	0.655	6.0	6x6	B	"	49	24.41	17.42	15.61	15.46	15.15
132	20-30	1/8-inch	5.0	0.675	0.675	0.675	5.1	6x6	D	1/8	48	27.85	19.90	17.65	17.56	17.20

Table 1.--SUMMARY OF RESULTS OF TESTS TO DETERMINE THE FLOW OF SAND AND THE LOSS OF HEAD, AT VARIOUS DISCHARGE RATES FOR DIFFERENT PACK-AQUIFER RATIOS, WHEN USED WITH WELL SCREENS OF DIVERSE TYPES AND DIFFERENT SCREEN OPENINGS.

Test no.	Sand size	Gravel size	Pack-aquifer ratio	Discharge Initial	Discharge Final	Discharge Average	Amount of sand moved	Interface screen	Well screen Type	Well screen Slot opening	Water temperature	Piezometric head in inches of water in manometers at final discharge No. 3	No. 5	No. 8	No. 13	No. 15
	U. S. sieve numbers	Inches or sieve numbers		GPM	GPM	GPM	Grams	Mesh per inch		Inch	Degree F					
				(Q_i)	(Q_f)	(Q_a)	(G)				(t)					
1	20-30	½-inch	16.2	0.325	0.325	0.325	5.6	10x10	B	3/16	57	21.57	17.28	16.57	16.56	16.55
2	"	"	"	0.650	0.640	0.645	7.0	"	"	"	56	27.77	16.68	14.57	14.55	14.52
3	"	"	"	1.30	1.26	1.28	45.9	"	"	"	54	38.71	15.13	9.87	9.85	9.76
4	"	"	"	2.48	2.70	2.59	38.1	"	"	"	50	70.0	31.12	21.35	21.23	20.97
5	"	"	"	0.315	0.315	0.315	3.5	"	C	0.200	53	13.01	8.53	7.83	7.82	7.81
6	"	"	"	0.640	0.630	0.635	6.3	"	"	"	53	25.33	15.25	12.74	12.72	12.69
7	"	"	"	1.31	1.27	1.29	28.7	"	"	"	53	39.64	15.87	10.35	10.28	10.22
8	"	"	"	2.48	2.70	2.59	92.8	"	"	"	52	66.80	29.22	20.70	20.57	20.35
9	"	"	"	0.325	0.325	0.325	3.8	"	D	3/16	52	11.30	7.22	6.46	6.44	6.42
10	"	"	"	0.645	0.635	0.640	3.5	"	"	"	51	25.39	15.50	13.63	13.62	13.62
11	"	"	"	1.30	1.27	1.28	27.6	"	"	"	53	37.53	14.90	10.06	10.03	9.98
12	"	"	"	2.54	2.76	2.65	126.5	"	"	"	51	64.5	27.30	22.28	22.15	21.89
135	20-30	½-inch	16.2	0.322	---	---	Wash out	6x6	B	3/16	--	---	---	---	---	---
13	20-30	¼-inch	8.1	0.325	0.320	0.322	2.6	10x10	B	3/16	56	7.02	3.03	2.17	2.14	2.11
14	"	"	"	0.655	0.640	0.648	4.6	"	"	"	52	28.29	16.82	14.28	14.24	14.13
15	"	"	"	1.29	1.29	1.29	14.9	"	"	"	47	44.27	17.76	11.30	11.06	10.77
16	"	"	"	2.50	2.66	2.58	12.9	"	"	"	46	70.8	32.62	20.41	20.12	19.31
17	"	"	"	0.325	0.325	0.325	2.9	"	C	0.100	52	13.15	8.58	7.66	7.64	7.60
18	"	"	"	0.645	0.640	0.642	3.2	"	"	"	50	27.91	16.29	13.72	13.67	13.57
19	"	"	"	1.30	1.27	1.28	13.9	"	"	"	48	43.85	16.77	10.58	10.41	10.12
20	"	"	"	2.46	2.62	2.54	35.1	"	"	"	48	72.4	29.44	19.55	19.00	18.32
21	"	"	"	0.325	0.325	0.325	3.5	"	D	3/16	50	6.78	1.66	0.89	0.87	0.84
22	"	"	"	0.660	0.645	0.652	3.8	"	"	"	49	29.37	16.41	14.22	14.16	14.05
23	"	"	"	1.30	1.26	1.28	13.1	"	"	"	48	45.88	16.57	10.46	10.36	10.08
24	"	"	"	2.50	2.66	2.58	32.2	"	"	"	48	75.	28.17	20.60	20.02	19.27
133	"	"	"	2.49	2.56	2.52	31.3	6x6	B	3/16	48	43.61	23.77	18.11	17.82	17.26
134	20-30	¼-inch	8.1	5.04	5.26	5.15	88.6	6x6	B	3/16	48	85.	45.90	39.41	37.76	36.22
25	20-30	1/8-inch	5.0	0.325	0.320	0.322	2.0	10x10	B	1/8	48	11.66	6.83	5.87	5.82	5.66
26	"	"	"	0.645	0.635	0.640	1.8	"	"	"	45	28.68	17.00	14.16	14.01	13.61
27	"	"	"	1.31	1.26	1.28	5.7	"	"	"	48	46.10	18.58	11.13	10.79	9.98
28	"	"	"	2.39	2.67	2.53	8.3	"	"	"	46	81.	36.18	23.32	21.97	19.74
29	"	"	"	0.320	0.315	0.318	2.6	"	C	0.040	51	6.15	1.47	0.20	0.15	0.00
30	"	"	"	0.650	0.645	0.648	6.6	"	"	"	48	30.50	17.12	14.26	14.12	13.72
31	"	"	"	1.31	1.27	1.29	7.1	"	"	"	47	48.00	18.70	11.29	10.99	10.18
32	"	"	"	2.51	2.72	2.62	7.5	"	"	"	42	77.5	37.43	24.00	22.88	20.73
33	"	"	"	0.325	0.320	0.322	3.3	"	D	1/8	51	26.54	22.58	21.96	21.90	21.75
34	"	"	"	0.660	0.645	0.652	2.7	"	"	"	47	28.85	16.73	14.89	14.76	14.41
35	"	"	"	1.32	1.29	1.30	5.2	"	"	"	45	44.47	17.80	12.46	12.12	11.27
36	"	"	"	2.49	2.61	2.55	8.6	"	"	"	44	70.7	31.67	21.54	20.44	18.44
131	"	"	"	0.655	0.655	0.655	6.0	6x6	B	"	49	24.41	17.42	15.61	15.48	15.15
132	20-30	1/8-inch	5.0	0.675	0.675	0.675	5.1	6x6	D	1/8	48	27.85	19.90	17.65	17.56	17.20

FERENT PACK-AQUIFER RATIOS, WHEN USED WITH ...

Test no.	Sand size	Gravel size	Pack-aquifer ratio	Discharge: Initial	Discharge: Final	Discharge: Average	Amount of sand moved	Inter-face screen	Well screen: Type	Well screen: Slot opening	Water temper-ature	Piezometric head in inches of water in manometers at final discharge: No. 3	No. 5	No. 8	No. 13	No. 15
	U. S. sieve numbers	Inches or sieve numbers		GPM	GPM	GPM	Grams	Mesh per inch		Inch	Degree F					
				(Q_i)	(Q_f)	(Q_a)	(G)				(t)					
37	30-40	1/16-inch	3.7	0.325	0.320	0.322	2.2	14x18	B	1/16	50	27.28	16.98	14.84	14.57	13.86
38	"	"	"	0.645	0.625	0.635	2.2	"	"	"	47	52.2	22.10	14.97	14.35	12.77
39	"	"	"	1.24	1.33	1.28	2.8	"	"	"	46	83.3	32.71	19.31	17.57	13.54
40	"	"	"	0.330	0.320	0.325	1.7	"	C	0.040	51	21.33	8.08	5.08	4.82	4.03
41	"	"	"	0.655	0.630	0.642	1.9	"	"	"	48	58.4	24.99	15.32	14.72	13.16
42	"	"	"	1.23	1.32	1.28	2.6	"	"	"	47	86.4	34.77	17.63	15.87	11.48
43	"	"	"	2.52	2.87	2.70	2.2	"	"	"	44	112.	56.3	41.17	36.73	25.62
44	"	"	"	0.325	0.320	0.322	5.7	"	D	1/16	46	28.99	17.29	14.68	14.39	13.61
45	"	"	"	0.655	0.645	0.650	1.5	"	"	"	46	57.3	24.37	16.49	15.86	14.20
46	"	"	"	1.23	1.26	1.24	2.7	"	"	"	45	81.3	32.19	15.98	14.35	10.40
47	30-40	1/16-inch	3.7	2.37	2.62	2.50	2.6	"	"	"	45	123.5	60.3	36.58	32.72	20.69
98	40-60	1/8-inch	11.7	0.325	0.325	0.325	19.0	6x6	B	1/16	46	28.62	8.32	5.48	5.42	5.25
99	"	"	"	0.645	0.655	0.650	42.1	"	"	"	44	62.9	26.63	15.82	15.53	15.16
100	"	"	"	1.28	1.33	1.30	83.7	"	"	"	43	88.5	28.57	15.12	13.92	13.07
101	"	"	"	0.325	0.320	0.322	15.9	"	B	1/8	48	32.27	13.45	10.03	9.96	9.80
102	"	"	"	0.640	0.645	0.642	73.9	"	"	"	48	69.5	24.58	15.36	14.56	14.21
103	"	"	"	1.29	1.36	1.32	221.1	"	"	"	48	101.	34.95	18.43	15.08	14.03
104	"	"	"	0.325	0.325	0.325	16.9	"	C	0.020	48	30.07	14.55	10.92	10.85	10.68
105	"	"	"	0.645	0.645	0.645	48.6	"	"	"	47	56.6	24.60	14.78	14.59	14.25
106	"	"	"	1.26	1.28	1.27	113.5	"	"	"	46	88.3	28.70	13.32	11.49	10.72
107	"	"	"	0.325	0.320	0.322	27.1	"	C	0.040	49	30.16	16.08	12.74	12.64	12.48
108	"	"	"	0.640	0.640	0.640	49.5	"	"	"	48	52.8	22.61	14.40	14.19	13.86
109	"	"	"	1.28	1.30	1.29	100.6	"	"	"	46	85.	26.26	13.47	12.05	11.24
110	"	"	"	0.325	0.320	0.322	18.5	"	C	0.100	50	30.01	10.65	7.39	7.16	7.01
111	"	"	"	0.645	0.650	0.648	71.5	"	"	"	48	67.3	24.78	15.62	14.69	14.33
112	"	"	"	1.30	1.39	1.34	199.2	"	"	"	48	96.5	33.48	18.93	15.18	14.36
113	"	"	"	0.325	0.325	0.325	25.6	"	D	1/16	50	---	17.23	12.66	12.57	12.41
114	"	"	"	0.650	0.650	0.650	59.5	"	"	"	49	55.8	26.01	16.31	15.37	15.02
115	"	"	"	1.28	1.30	1.29	156.2	"	"	"	48	84.8	30.79	15.85	12.74	11.91
116	"	"	"	0.325	0.320	0.322	26.2	"	D	1/8	51	32.67	17.31	11.57	11.51	11.37
117	"	"	"	0.655	0.660	0.658	73.6	"	"	"	49	60.	28.26	17.13	16.13	15.81
118	40-60	1/8-inch	11.7	1.28	1.31	1.30	143.3	"	"	"	49	87.5	31.20	14.93	12.97	12.13
136	40-60	8-10	7.6	0.320	0.315	0.318	6.3	6x6	C	0.020	53	22.87	8.62	3.80	3.70	3.42
137	"	"	"	0.655	0.665	0.660	7.9	"	"	"	53	51.5	25.64	17.26	17.05	16.47
138	"	"	"	1.25	1.27	1.26	10.9	"	"	"	52	96.	21.62	11.88	11.43	10.21
139	"	"	"	2.41	2.43	2.42	12.6	"	"	"	52	127.5	35.55	17.47	16.45	13.87
140	"	"	"	0.325	0.320	0.322	5.6	"	D	1/16	54	21.36	8.98	5.44	5.37	5.08
141	"	"	"	0.640	0.645	0.642	7.6	"	"	"	53	48.76	23.00	14.97	14.76	14.17
142	"	"	"	1.28	1.30	1.29	8.5	"	"	"	53	75.	25.77	13.68	13.24	11.98
143	"	"	"	2.49	2.54	2.52	9.6	"	"	"	52	134.	38.18	21.60	20.58	17.77
148	"	"	"	1.28	1.32	1.30	13.2	"	"	"	54	78.0	30.17	14.36	13.76	12.44
149	40-60	8-10	7.6	2.54	2.64	2.59	14.6	"	"	"	53	140.5	44.30	24.24	22.95	19.97

Table 2.--SUMMARY OF DATA FOR PLOTTING AMOUNT OF SAND MOVED, HYDRAULIC GRADIENT IN SAND, AND HEAD LOSS IN GRAVEL PACK AT DIFFERENT PACK-AQUIFER RATIOS AND DIFFERENT DISCHARGES.

Test No.	Sand size	Gravel size	Pack-aquifer ratio	Average discharge	Porosity of the sand	Average velocity in sand pores	Amount of sand moved: Test run	Amount of sand moved: Per square foot of interface	Final discharge	Head loss in sand between taps 3 and 5	Hydraulic gradient in sand between taps 3 and 5	Head loss in gravel between taps 8 and 15
	U.S. sieve numbers	Inches or sieve numbers		GPM		ft/sec	Grams	Grams per square foot	GPM	Inches		Inches
				(Q_a)	(n_s)	(V_a)	(G)	$\frac{G}{Ft^2}$	(Q_f)	$(H_{L_{3-5}})$	(i_{3-5})	$(H_{L_{8-15}})$
1	20-30	½-inch	16.2	0.325	0.445	0.00903	5.6	31.3	0.325	4.29	0.968	0.02
2	"	"	"	0.645	"	.0179	7.0	39.1	0.640	11.09	2.50	0.05
3	"	"	"	1.28	"	.0356	45.9	256.	1.26	23.58	5.32	0.11
4	"	"	"	2.59	"	.0720	38.1	213.	2.70	38.9	8.78	0.38
5	"	"	"	0.315	"	.00875	3.5	19.5	0.315	4.48	1.011	0.02
6	"	"	"	0.635	"	.0177	6.3	35.2	0.630	10.08	2.27	0.05
7	"	"	"	1.29	"	.0359	28.7	160.	1.27	23.77	5.36	0.13
8	"	"	"	2.59	"	.0720	92.8	518.	2.70	37.58	8.48	0.35
9	"	"	"	0.325	"	.00903	3.8	21.2	0.325	4.08	0.921	0.04
10	"	"	"	0.640	"	.0178	3.5	19.5	0.635	9.89	2.23	0.01
11	"	"	"	1.28	"	.0356	27.6	154.	1.27	22.63	5.10	0.09
12	"	"	"	2.65	"	.0736	126.5	707.	2.76	37.2	8.39	0.37
135	20-30	½-inch	16.2	0.322	0.445	0.00895	Wash out	Wash out	0.322	---	---	---
13	20-30	¼-inch	8.1	0.322	0.445	0.00895	2.6	14.5	0.320	3.99	0.900	0.06
14	"	"	"	0.648	"	.0180	4.6	25.7	0.640	11.47	2.58	0.15
15	"	"	"	1.29	"	.0359	14.9	83.2	1.29	26.51	5.97	0.53
16	"	"	"	2.58	"	.0717	12.9	72.1	2.66	38.2	8.62	1.10
17	"	"	"	0.325	"	.00903	2.9	16.2	0.325	4.57	1.031	0.06
18	"	"	"	0.642	"	.0179	3.2	17.9	0.640	11.62	2.62	0.15
19	"	"	"	1.28	"	.0356	13.9	77.7	1.27	27.08	6.11	0.46
20	"	"	"	2.54	"	.0706	35.1	196.	2.62	43.0	9.70	1.23
21	"	"	"	0.325	"	.00903	3.5	19.5	0.325	5.12	1.15	0.05
22	"	"	"	0.652	"	.0181	3.8	21.2	0.645	12.96	2.92	0.17
23	"	"	"	1.28	"	.0356	13.1	73.2	1.26	29.31	6.60	0.38
24	"	"	"	2.58	"	.0717	32.2	180.	2.66	47.	10.60	1.33
133	"	"	"	2.52	"	.0701	31.3	175.	2.56	19.84	4.47	0.85
134	20-30	¼-inch	8.1	5.15	0.445	0.143	88.6	495.	5.26	39.	8.80	3.19
25	20-30	1/8-inch	5.0	0.322	0.445	0.00895	2.0	11.2	0.320	4.83	1.09	0.21
26	"	"	"	0.640	"	.0178	1.8	10.1	0.635	11.68	2.63	0.55
27	"	"	"	1.28	"	.0356	5.7	31.8	1.26	27.52	6.20	1.15
28	"	"	"	2.53	"	.0703	8.3	46.4	2.67	45.	10.15	3.58
29	"	"	"	0.318	"	.00884	2.6	14.5	0.315	4.68	1.06	0.20
30	"	"	"	0.648	"	.0180	6.6	36.8	0.645	13.38	3.02	0.54
31	"	"	"	1.29	"	.0359	7.1	39.6	1.27	29.30	6.60	1.11
32	"	"	"	2.62	"	.0728	7.5	41.9	2.72	40.1	9.05	3.27
33	"	"	"	0.322	"	.00895	3.3	18.4	0.320	3.96	0.893	0.21
34	"	"	"	0.652	"	.0181	2.7	15.1	0.645	12.12	2.73	0.48
35	"	"	"	1.30	"	.0362	5.2	29.0	1.29	26.67	6.01	1.19
36	"	"	"	2.55	"	.0709	8.6	48.0	2.61	39.0	8.80	3.10
131	"	"	"	0.655	"	.0182	6.0	33.	0.655	6.99	1.58	0.46
132	20-30	1/8-inch	5.0	0.675	0.445	0.0188	5.1	28.5	0.675	7.95	1.79	0.45
73	30-40	¼-inch	12.7	0.315	0.445	0.00875	10.3	57.5	0.310	10.61	2.39	0.09
74	"	"	"	0.660	"	.0184	80.6	450.	0.660	24.09	5.43	0.47
75	"	"	"	1.28	"	.0356	328.7	1837.	1.29	29.3	6.60	3.08
76	"	"	"	0.318	"	.00884	14.9	83.3	0.315	13.78	3.10	0.21
77	"	"	"	0.650	"	.0181	41.1	229.	0.645	26.90	6.06	0.34
78	"	"	"	1.28	"	.0356	249.8	1396.	1.30	40.6	9.15	2.45
79	"	"	"	0.322	"	.00895	13.7	76.5	0.320	12.22	2.76	0.08
80	"	"	"	0.648	"	.0180	99.4	555.	0.645	30.36	6.85	0.68
81	"	"	"	1.32	"	.0367	466.7	2610.	1.34	48.	10.82	5.04
82	"	"	"	0.318	"	.00884	13.9	77.7	0.310	11.47	2.58	0.06
83	"	"	"	0.652	"	.0181	47.4	265.	0.650	23.03	5.19	0.16
84	30-40	¼-inch	12.7	1.29	0.445	0.0359	201.9	1129.	1.30	35.8	8.07	2.58

Table 2.--SUMMARY OF DATA FOR PLOTTING AMOUNT OF SAND MOVED, HYDRAULIC GRADIENT IN SAND, AND HEAD LOSS IN GRAVEL PACK AT DIFFERENT PACK-AQUIFER RATIOS AND DIFFERENT DISCHARGES.--Continued

Test No.	Sand size	Gravel size	Pack-aquifer ratio	Average discharge	Porosity of the sand	Average velocity in sand pores	Amount of sand moved: Test run	Amount of sand moved: Per square foot of interface	Final discharge	Head loss in sand between taps 3 and 5	Hydraulic gradient in sand between taps 3 and 5	Head loss in gravel between taps 8 and 15
	U.S. sieve numbers	Inches or sieve numbers		GPM		ft/sec	Grams	Grams per square foot	GPM	Inches		Inches
				(Q_a)	(n_s)	(V_a)	(G)	$\frac{G}{Ft^2}$	(Q_f)	$(H_{L_{3-5}})$	(i_{3-5})	$(H_{L_{8-15}})$
48	30-40	1/8-inch	7.8	0.322	0.445	0.00895	3.0	16.8	0.320	12.53	2.83	0.22
49	"	"	"	0.660	"	.0184	7.4	41.3	0.655	31.2	7.03	0.54
50	"	"	"	1.27	"	.0353	13.2	73.8	1.29	47.3	10.68	1.41
51	"	"	"	2.61	"	.0725	9.2	51.4	2.73	55.5	12.52	3.44
52	"	"	"	0.320	"	.00889	2.8	15.6	0.315	11.75	2.65	0.24
53	"	"	"	0.650	"	.0181	5.9	33.0	0.650	27.8	6.26	0.53
54	"	"	"	1.29	"	.0359	17.4	97.2	1.31	47.3	10.68	1.26
55	"	"	"	2.60	"	.0723	13.7	76.6	2.73	59.5	13.42	3.93
56	"	"	"	0.322	"	.00895	4.4	24.6	0.320	11.47	2.58	0.22
57	"	"	"	0.652	"	.0181	6.4	35.8	0.650	28.7	6.47	0.51
58	"	"	"	1.29	"	.0359	25.9	145.	1.31	52.5	11.83	1.27
59	"	"	"	2.55	"	.0709	15.3	85.5	2.67	64.	14.4	3.87
60	"	"	"	2.52	"	.0701	7.7	43.0	2.57	56.5	12.74	3.03
61	"	"	"	0.325	"	.00903	5.1	28.5	0.325	11.78	2.66	0.24
62	"	"	"	0.645	"	.0179	8.4	46.9	0.640	25.1	5.66	0.55
63	"	"	"	1.30	"	.0362	17.1	95.5	1.32	39.3	8.86	1.38
64	"	"	"	2.57	"	.0714	19.3	108.	2.66	58.5	13.2	3.35
65	"	"	"	0.325	"	.00903	6.6	36.8	0.325	9.90	2.23	0.22
66	"	"	"	0.650	"	.0181	12.0	67.0	0.650	23.54	5.30	0.54
67	"	"	"	1.28	"	.0356	33.5	187.	1.28	41.5	9.36	1.30
68	"	"	"	2.57	"	.0714	30.7	171.5	2.65	60.	13.5	3.46
69	"	"	"	0.322	"	.00895	4.8	26.8	0.320	11.52	2.60	0.34
70	"	"	"	0.652	"	.0181	11.0	61.5	0.650	30.6	6.90	0.54
71	"	"	"	1.30	"	.0362	19.1	107.	1.32	42.8	9.65	1.38
72	"	"	"	2.60	"	.0723	23.7	132.	2.72	55.	12.4	3.24
119	"	"	"	0.322	"	.00895	5.0	27.9	0.320	9.07	2.04	0.19
120	"	"	"	0.652	"	.0181	9.3	51.9	0.650	22.76	5.14	0.47
121	"	"	"	1.30	"	.0362	28.3	158.	1.31	38.5	8.68	1.45
122	"	"	"	2.62	"	.0728	25.6	143.	2.72	48.	10.82	2.85
123	"	"	"	0.325	"	.00903	5.7	31.8	0.325	9.05	2.04	0.22
124	"	"	"	0.652	"	.0181	9.0	50.3	0.650	20.38	4.59	0.45
125	"	"	"	1.29	"	.0359	23.7	132.	1.30	36.9	8.32	1.21
126	"	"	"	2.58	"	.0717	21.8	122.	2.67	46.5	10.49	2.82
127	"	"	"	0.322	"	.00895	6.6	36.8	0.320	9.57	2.16	0.18
128	"	"	"	0.645	"	.0179	10.2	57.0	0.640	20.07	4.57	0.52
129	"	"	"	1.29	"	.0359	27.6	154.	1.30	34.8	7.85	1.43
130	30-40	1/8-inch	7.8	2.56	0.445	0.0711	26.7	149.	2.62	49.5	11.17	3.24
37	30-40	1/16-inch	3.7	0.322	0.445	0.00895	2.2	12.3	0.320	10.30	2.32	0.98
38	"	"	"	0.635	"	.0177	2.2	12.3	0.625	30.1	6.78	2.20
39	"	"	"	1.28	"	.0356	2.8	15.6	1.33	50.6	10.42	5.77
40	"	"	"	0.325	"	.00903	1.7	9.5	0.320	13.25	2.98	1.05
41	"	"	"	0.642	"	.0179	1.9	10.6	0.630	33.4	7.54	2.16
42	"	"	"	1.28	"	.0356	2.6	14.5	1.32	51.6	11.63	6.15
43	"	"	"	2.70	"	.0751	2.2	12.3	2.87	66.	14.9	15.55
44	"	"	"	0.322	"	.00895	5.7	31.8	0.320	11.70	2.64	1.07
45	"	"	"	0.650	"	.0181	1.5	8.4	0.645	32.9	7.42	2.29
46	"	"	"	1.24	"	.0345	2.7	15.1	1.26	49.1	11.08	5.58
47	30-40	1/16-inch	3.7	2.50	0.445	0.0695	2.6	14.5	2.62	63.	14.2	15.89
98	40-60	1/8-inch	11.7	0.325	0.437	0.00923	19.0	106.	0.325	20.30	4.58	0.23
99	"	"	"	0.650	"	.0185	42.1	235.	0.655	36.3	8.19	0.66
100	"	"	"	1.30	"	.0369	83.7	468.	1.33	60.	13.54	2.05
101	"	"	"	0.322	"	.00914	15.9	88.8	0.320	18.82	4.25	0.23
102	"	"	"	0.642	"	.0182	73.9	412.	0.645	45.	10.16	1.15
103	"	"	"	1.32	"	.0375	221.1	1236.	1.36	66.	14.90	4.40
104	"	"	"	0.322	"	.00923	16.9	94.5	0.325	15.52	3.50	0.24
105	"	"	"	0.645	"	.0183	48.6	272.	0.645	32.0	7.22	0.53
106	"	"	"	1.27	"	.0361	113.5	634.	1.28	59.6	13.46	2.60
107	"	"	"	0.322	"	.00914	27.1	151.	0.320	14.08	3.18	0.26
108	"	"	"	0.640	"	.0182	49.5	276.	0.640	30.2	6.81	0.54
109	"	"	"	1.29	"	.0366	100.6	562.	1.30	59.	13.32	2.23
110	"	"	"	0.322	"	.00914	18.5	103.	0.320	19.36	4.37	0.38
111	"	"	"	0.648	"	.0184	71.5	399.	0.650	42.5	9.59	1.39
112	"	"	"	1.34	"	.0380	199.2	1113.	1.39	63.0	14.22	4.57
113	"	"	"	0.325	"	.00923	25.6	143.	0.325	---	---	0.25
114	"	"	"	0.645	"	.0185	59.5	332.	0.650	29.8	6.72	1.29
115	"	"	"	1.29	"	.0366	156.2	873.	1.30	54.	12.19	3.94
116	"	"	"	0.322	"	.00914	26.2	146.	0.320	15.36	3.46	0.20
117	"	"	"	0.658	"	.0187	73.6	411.	0.660	31.5	7.11	1.32
118	40-60	1/8-inch	11.7	1.30	0.437	0.0369	143.3	801.	1.31	56.3	12.71	2.82

Table 2.--SUMMARY OF DATA FOR PLOTTING AMOUNT OF SAND MOVED, HYDRAULIC GRADIENT IN SAND, AND HEAD LOSS IN GRAVEL PACK AT DIFFERENT PACK-AQUIFER RATIOS AND DIFFERENT DISCHARGES.--Continued

Test No.	Sand Size	Gravel size	Pack-aquifer ratio	Average discharge	Porosity of the sand	Average velocity in sand pores	Amount of sand moved: Test run	Amount of sand moved: Per square foot of interface	Final discharge	Head loss in sand between taps 3 and 5	Hydraulic gradient in sand between taps 3 and 5	Head loss in gravel between taps 8 and 15
	U.S. sieve numbers	Inches or sieve numbers		GPM		ft/sec	Grams	Grams per square foot	GPM	Inches		Inches
				(Q_a)	(n_s)	(V_a)	(G)	$\frac{G}{Ft^2}$	(Q_f)	$(H_{L_{3-5}})$	$(i_{3-5}$	$(H_{L_{8-15}})$
136	40-60	8-10	7.6	0.318	0.437	0.00903	6.3	35.2	0.315	14.25	3.22	0.38
137	"	"	"	0.660	"	.0188	7.9	44.1	0.665	26.	5.86	0.79
138	"	"	"	1.26	"	.0358	10.9	60.9	1.27	74.5	16.81	1.67
139	"	"	"	2.42	"	.0687	12.6	70.4	2.43	91.9	20.75	3.60
140	"	"	"	0.322	"	.00914	5.6	31.3	0.320	12.38	2.79	0.36
141	"	"	"	0.642	"	.0182	7.6	42.4	0.645	25.76	5.81	0.80
142	"	"	"	1.29	"	.0366	8.5	47.5	1.30	49.	11.06	1.70
143	"	"	"	2.52	"	.0716	9.6	53.6	2.54	96.	21.65	3.83
148	"	"	"	1.30	"	.0369	13.2	73.8	1.32	47.8	10.77	1.92
149	40-60	8-10	7.6	2.59	0.437	0.0735	14.6	81.6	2.64	96.	21.6	4.27
85	40-60	1/16-inch	5.5	0.320	0.437	0.00908	2.8	15.6	0.315	17.96	4.05	0.99
86	"	"	"	0.652	"	.0185	4.9	27.4	0.660	44.9	10.13	2.87
87	"	"	"	1.32	"	.0375	4.0	22.4	1.38	65.	14.67	5.93
88	"	"	"	0.322	"	.00914	7.7	43.0	0.320	17.98	4.05	1.10
89	"	"	"	0.642	"	.0182	6.4	35.8	0.645	39.5	8.91	2.50
90	"	"	"	1.30	"	.0369	8.6	48.0	1.33	63.	14.21	6.45
91	"	"	"	0.322	"	.00914	2.5	14.0	0.320	18.07	4.07	1.04
92	"	"	"	0.645	"	.0183	2.8	15.6	0.650	34.6	7.80	1.98
93	"	"	"	1.28	"	.0364	3.0	16.8	1.30	60.5	13.55	4.84
94	"	"	"	0.325	"	.00923	5.3	29.6	0.325	14.11	3.18	1.00
95	"	"	"	0.642	"	.0182	4.1	22.9	0.645	29.5	6.65	2.05
96	"	"	"	1.28	"	.0364	6.9	38.5	1.29	57.	12.86	5.20
97	40-60	1/16-inch	5.5	2.03	0.437	0.0577	6.3	35.2	2.05	92.	20.75	9.97
144	40-60	14-16	4.5	0.325	0.437	0.00923	3.0	16.8	0.325	11.64	2.63	1.42
145	"	"	"	0.650	"	.0185	2.2	12.3	0.655	23.42	5.28	2.75
146	"	"	"	1.27	"	.0361	2.2	12.3	1.28	45.1	10.18	5.64
147	"	"	"	2.46	"	.0699	2.7	15.1	2.49	90.	20.3	11.50
150	"	"	"	0.322	"	.00914	1.3	7.3	0.320	12.41	2.79	1.39
151	"	"	"	0.640	"	.0182	1.2	6.7	0.640	23.90	5.38	2.70
152	"	"	"	1.29	"	.0366	1.3	7.3	1.30	48.	10.81	5.86
153	40-60	14-16	4.5	2.45	0.437	0.0681	1.5	8.4	2.47	91.	20.5	10.70

476244