EFFECT OF WELL SCREENS AND GRAVEL ENVELOPES ON FLOW OF SAND INTO WELLS

(Progress Report on Performance of Well Screen Project)

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U. S. DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE

Robert M. Salter, Chief

PROGRESS REPORT

on the

PERFORMANCE OF WELL SCREENS

EFFECT OF WELL SCREENS AND GRAVEL ENVELOPES

ON FLOW OF SAND INTO WELLS

by

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Soil Conservation Service
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A contribution from the
Division of Irrigation Engineering and Water Conservation
and
Colorado Agricultural Experiment Station
in cooperation with the
Well Screen Manufacturers

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Progress Report
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INTRODUCTION

Water-bearing formations capable of supplying water for irrigation wells are usually made up of fine sand with varying amounts of coarser material. Because irrigation wells must furnish large quantities of water, the rate of flow through the sand adjacent to the well is relatively high. If the velocity is high enough to move the sand particles they will be carried toward the well, and unless provision is made for controlling the movement of sand by means of properly designed screens or combinations of screens and gravel envelopes, excessive quantities of sand will be pumped which may ultimately cause the failure of the well. Furthermore, pumping sand shortens the life of the pump because of the wear on the impeller and bearings. In view of these facts, the study of the flow of sand into wells was included as a part of the Well Screen Investigations being conducted by the Division of Irrigation Engineering and Water Conservation of the Soil Conservation Service in cooperation with Colorado Agricultural Experiment Station, Colorado A and M College, and certain Well Screen Manufacturers.

The major objectives of this project are:

(1) To determine the loss of head through various types of well screens

with and without gravel envelopes under a wide range of flow conditions for the purpose of finding which types of screens are hydraulically most efficient.

(2) To determine the characteristics of well screens and gravel envelopes that will be most efficient in reducing the flow of sand and increasing the flow of water into the well with a minimum loss of head.

(3) To determine the effectiveness of the natural gravel envelope formed by surging or other means when suitable material occurs in the aquifer.

The present report deals with the last two objectives of the study.

Two progress reports have been submitted previously which give the results of studies concerning the first objective of the investigation. The report on Hydraulic Properties of Well Screens by Gilbert Corey, dated June 1949, is based on tests of the loss of head through various types of well screens with and without gravel envelopes. This report shows that increasing the percentage of openings reduces the loss through the screen up to a certain point beyond which further increases in the percentage of openings have no effect on the loss. Within the range tested this percentage is the same for all types of screens regardless of the quantity pumped or the size of gravel used in the envelope.

The report on Effect of Well Screens on Flow into Wells by Jack S. Peterson, dated January 1952, is a study of the theoretical law of flow into wells and includes experimental data confirming the law. As a result of the study, a formula was developed which indicates that there are other limiting factors in addition to the percentage of openings which, beyond a certain point, do not have any effect in reducing the losses through the screen. These factors are the length and diameter of the screen. The special tests made to check the validity of this formula showed that the theoretical formula and the experimental data were in close agreement. The theoretical formula also shows why increasing the percentage of openings in the screen does not decrease the loss through the screen beyond a definite limit.

The results of the studies previously reported were all based on full scale tests of screens and it was thought that the flow of sand into wells could be investigated in the same way. An attempt was made to conduct full scale tests, but it was found that the labor of handling the large quantities of sand and gravel required, made the cost prohibitive. In view of this fact it was decided to conduct the preliminary tests in a model. The results of the model studies would be used as the basis for determining which screen and gravel combinations were the most effective in controlling the flow of sand of a particular size. Full scale tests of these combinations would later be made to determine whether these combinations were effective in controlling the flow of sand under the conditions actually found in awell. In addition to these tests, investigations would be conducted to determine whether a satisfactory gravel envelope could be obtained by proper development of a water bearing sand made up of sizes ranging from fine to coarse. These studies also would be made in a model similar to that used in the tests of the flow of sand. The results of these investigations are discussed in this report.

FLOW OF SAND INTO WELLS

In the tests of the flow of sand into wells, the basis of comparison was the amount of sand washed out of the formation at different velocities in a definite time for various combinations of sands, gravel envelopes and screens. Sand and gravel with particles of uniform size were used in the tests. The effectiveness of the various combinations of sand, gravel and well screen was compared on the basis of the amount of sand moved under the different conditions in the model.

In a true model all the parts have to be proportioned according to the laws of similitude. Because of the difficulties that would be encountered in building scale models of the screens and in determining the sizes of gravel and sand to be used, a different plan was adopted for this study.

In was assumed that tests of the flow of sand through a horizontal pipe in which the sand, gravel and screen were placed in the same manner as they would occur in a well, would give comparative indications of the amount of sand movement at different velocities. For these tests the sands and gravels would be the same as those used for the full scale tests and the screens would be circular disks cut from standard screens. The discharge would be reduced so that the velocity through the sand and gravel would be the same as that in the prototype.

It was recognized that the flow lines in the model would be parallel whereas they should be radial if they were to conform to the flow in the prototype*. However, it was decided that it would be better to disregard this fact in these tests rather than to attempt to build a model with a converging section because any errors caused by this difference would be corrected when the final full scale tests were made. Furthermore, since all the model studies were to be made in the same way, the relative effec-

* Hydraulics of Wells, Utah State Agricultural Experiment Station Technical Bulletin 351, by Dean F. Peterson, Orson W. Israelsen and Vaughn E. Hanson, 1952.

tiveness of the different sand, gravel and screen combinations would be apparent from the tests.

Equipment for Study of Flow of Sand into Wells

A clear plastic tube 6 inches in diameter (O.D.) and 52 inches long was used for the tests of the flow of sand into wells. (See figure 1.) The ends of the tube were closed by means of plates with recessed grooves containing rubber gaskets. Four rods with wing nuts were used to clamp the plates on the ends of the tube. By tightening the wing nuts a watertight seal was obtained. This arrangement made it possible to assemble and dismantle the equipment quickly. Each plate was equipped with hose connections for the water supply. The rate of flow was controlled by valves in the inlet and outlet pipes.

Piezometer connections for measuring the head in the plastic tube were provided at the points shown in figure 1. The piezometers consisted of short pieces of brass tubing 1/8-inch in diameter (O.D.) which were driven into holes drilled in the plastic tube until flush with the inside of the plastic tube. Since the plastic tube was only 1/8-inch thick a boss was welded to the tube at each hole. The ends of the piezometers were turned true in a lathe and a disk of fine mesh screen was soldered on the end of each piezometer to keep sand from entering the opening.

Pressures were measured with manometers consisting of 3/8-inch glass tubing (I.D.) mounted on a board as shown in figure 1. Standard cross-section paper with 1/10-inch divisions was cemented to the manometer board back of the tubes for reading the pressures. Connections between the piezometers were made with rubber tubes. The assembled equipment is shown in figure 2. In order to eliminate the errors due to differences in the diameters of the

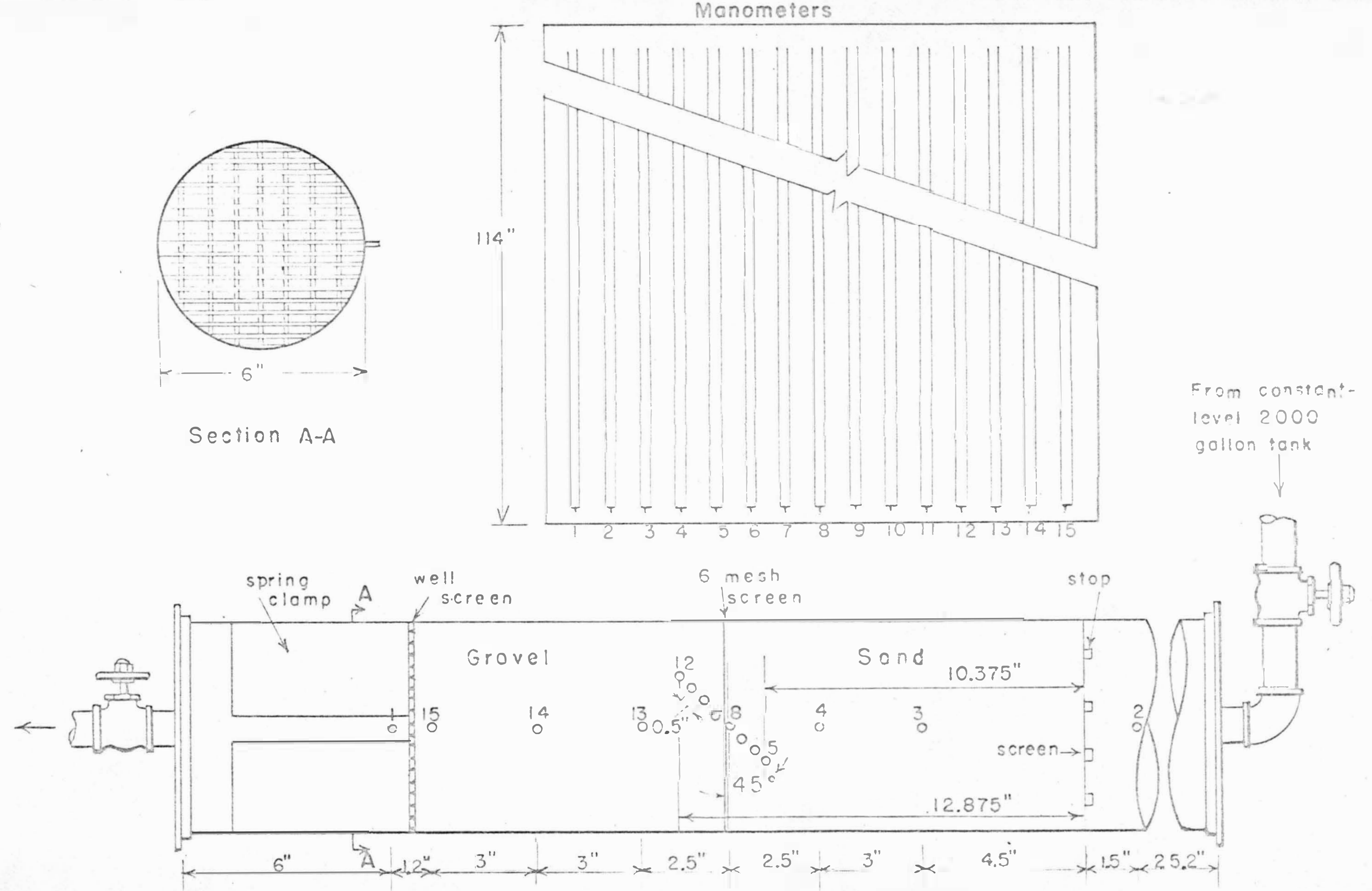

Figure 1 .- Equipment for making model study of flow of sand into wells.

glass tubes, corrections were applied to the readings of the manometers that were off size.

Water for the tests was drawn from a 2000 gallon constant-level tank set 6 feet above the floor of the test area. This tank was filled with city water which was kept in the tank continuously so that it would have the same temperature as the laboratory and consequently would have no tendency to give up or absorb air. During tests a small stream of city water was turned into the tank to keep the level constant. Two four-inch pipes set vertically with the open ends at the desired level, provided spillways for excess water coming into the tank. Since the amount of water used in the tests as well as the inflow was small, a fairly constant temperature of water was maintained.

A head of 10 feet was available from the tank. Because this head was too small to drive the required quantity of water through the model when testing fine sand, water at city pressure was used for these tests. A mercury manometer was used to measure the head when it was necessary to apply city pressure.

Small squares of standard screens were furnished by the manufacturers for the tests. Slightly oversize disks were sawed from these squares. These disks were ground accurately to size so that they would fit snugly in the plastic tube. Similar disks of 4-mesh heavy wire screen were made to hold the sand and gravel in place in the plastic tube. Stops were welded on the inside of the tube to hold the wire-mesh screens in position. The well screen was held in place by a collapsible metal sleeve that fitted inside the plastic tube. Since it was not possible to make the total length of the column of sand and gravel exactly the same for each test the collap-

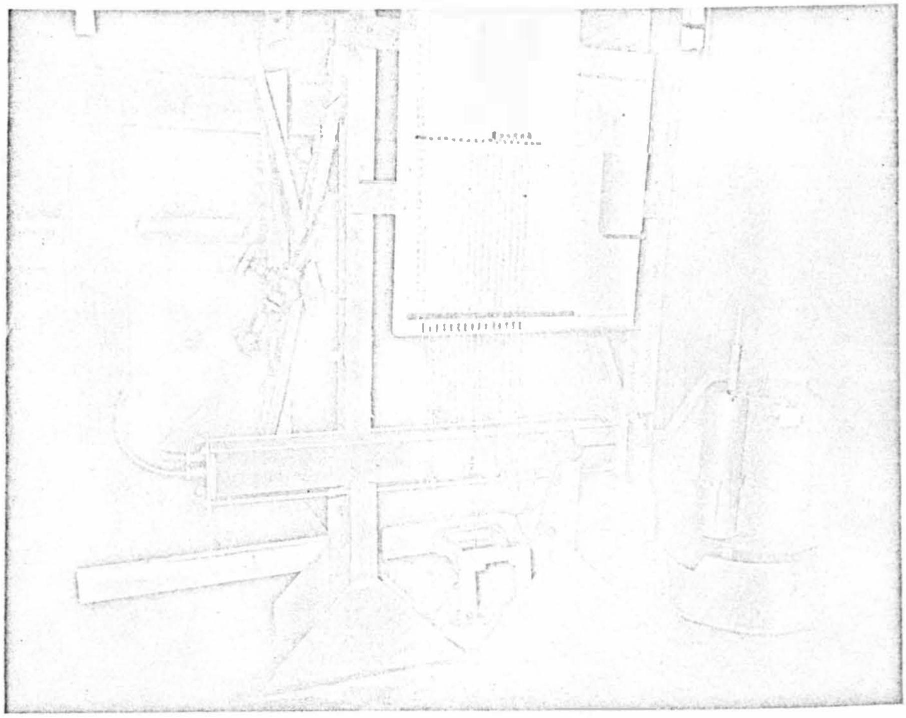

Figure 2.-- Arrangement of equipment for model study of flow of sand into wells.

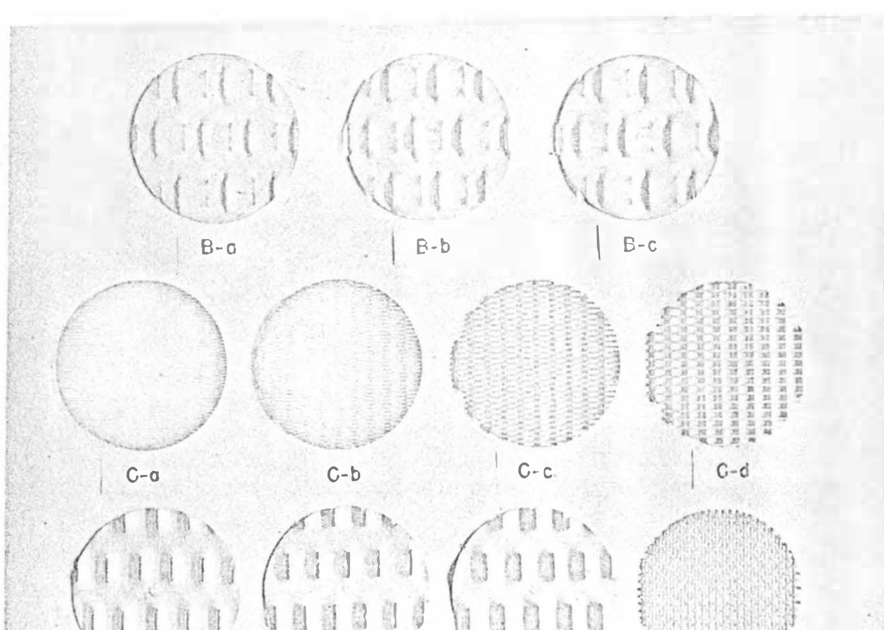

Figure 3.-- Screens used in tests. Disks were cut from standard well screens.

sible sleeve provided a means of holding the well screen firmly against the gravel. It also made it possible to remove the screen easily.

The following screens were tested:

(1) Type B, Lattice screens with 1/16, 1/8 and 3/16-inch perforations.

(2) Type C, Continuous slot screens with, 0.02, .04, .10 and .20-inch slots.

(3) Type D, Punched screens with 1/16, 1/8 and 3/16-inch perforations.

(4) Type F, Mesh screen with 0.145 inch openings.

Disks cut from screens of the types used in the tests, are shown in figure 3. The characteristics of these screens are given in table 1.

Sand and Gravel

The sand and gravel used for the tests consisted of water worn material from a local gravel pit. This material was formed by the wearing down of granite rocks in the river and is very durable. It was washed and screened approximately to size at the pit. After being dried this material was screened more closely to size by collecting the part retained between screens of the proper size.

The gravel used for the gravel envelopes in the model studies consisted of the 1/16, 1/8, 1/4 and 1/2-inch sizes. Even after careful screening the particles were not all of the exact sizes indicated. To determine the characteristics of the gravel more closely, a detailed screen analysis was made of a sample of each size. The screen analysis of the different sizes is shown in figure 4, and the diameters of the 50 percent sizes are given in table 2. Samples of the various sizes of sand and gravel are shown in figure 5.

Table 1.-- Characteristics of Well Screens used in Tests.

Symbol	Type	Material	Slot Width	Percent Open 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	.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	.145	33.64

* These values are the percentages of open area for screens 1 foot in diameter. The percentages for the disks of punched and twin-flow screens tested in the model are somewhat higher because the perforations were uniformly spaced over the entire area.

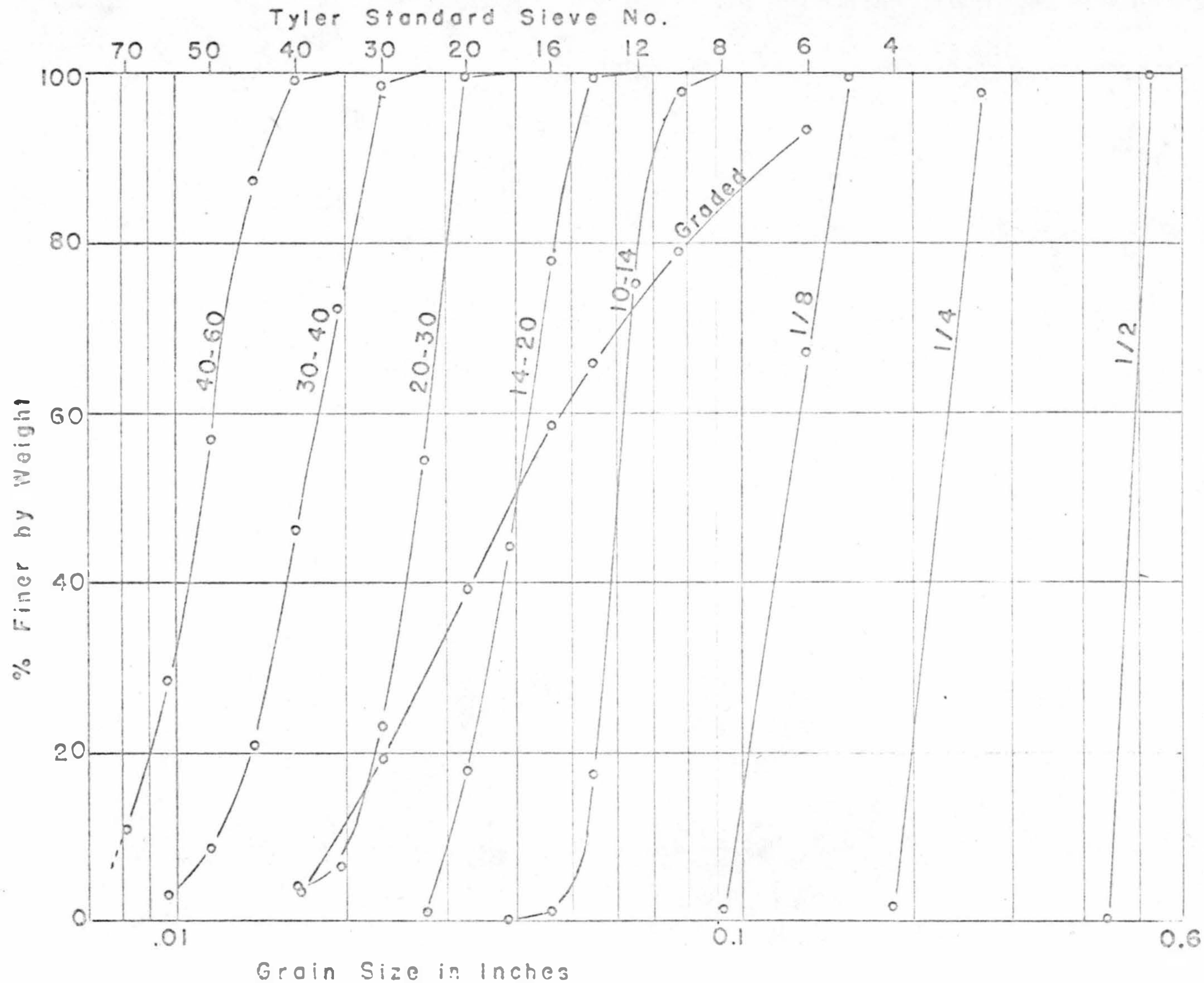

Figure 4 .- Screen analysis of sands and gravels.

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Table 2.-- Characteristics of sands and gravels used in tests

Classification	50-percent size Inch	Porosity
40-60 Sand	0.0112	0.400
30-40 Sand	.0169	.415
20-30 Sand	.027	.427
14-20 Sand	.040	.430
10-14 Sand*	.060	.422
1/8-inch Gravel	.120	.414
1/4-inch Gravel	.222	.395
1/2-inch Gravel	.483	.397

* Also used as 1/16-inch gravel.

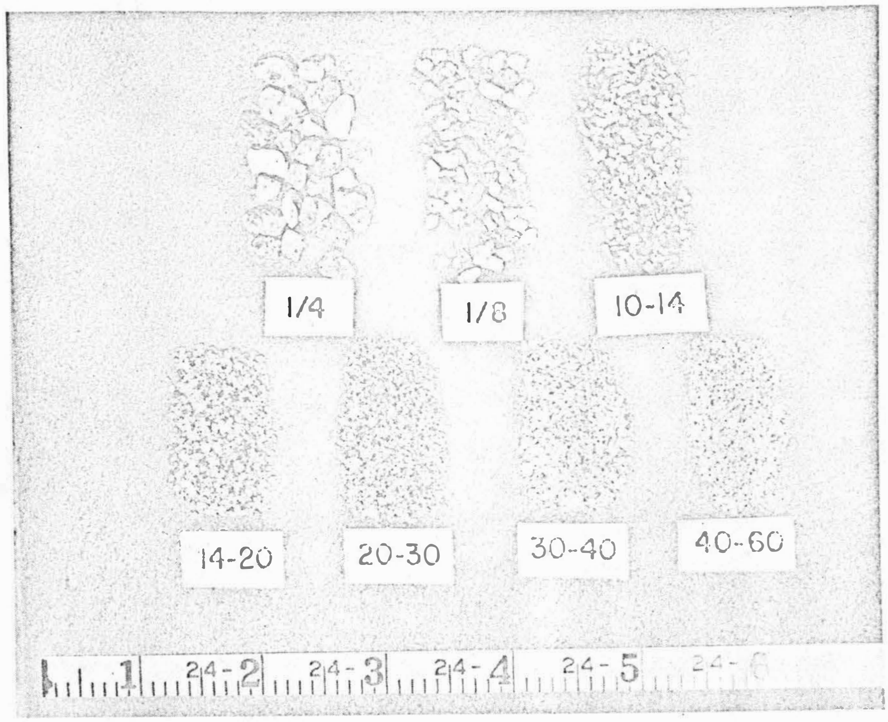

Figure 5.-- Samples of sand and gravel used in model study.

For the water bearing formation sands of the sizes retained between, the following standard screens were used: 10-14, 14-20, 20-30, 30-40 and 40-60. The analysis of the sand also, is shown in figure 4 and table 2.

According to tests on protective filters made by the Earth Materials Laboratory of the Bureau of Reclamation*, the ratio of the 50-percent grain size of the filter material to the 50-percent grain size of the base material should be between the limits 5 and 10, when uniform grain-size materials are used. For the tests on the flow of sand the ratios of the 50-percent size of the gravel in the gravel envelope to the 50-percent size of the sand in the formation were as follows:

Gravel Size Inch	Sand Size Screen No.	Ratio Gravel/sand	Gravel Size Inch	Sand Size Screen No.	Ratio Gravel/sand
1/16	20-30	2.4	1/4	10-14	3.4
1/16	30-40	3.4	1/4	14-20	5.2
1/16	40-60	5.1	1/4	20-30	8.0
1/8	14-20	2.6	1/4	30-40	11.3
1/8	20-30	4.0	1/4	40-60	17.2
1/8	30-40	5.6	1/2	10-14	7.4
1/8	40-60	8.6	1/2	14-20	11.3
			1/2	20-30	14.1

These ratios show that the full range of ratios recommended by the Bureau of Reclamation was covered except in the case of the 1/16-inch gravel where a fine sand should have been included.

Because the velocity in the model for a particular sand depends on the porosity of the sand, the material used in the experiments was tested for porosity. The porosity was determined by immersion in water. The results

* Laboratory Tests on Protective Filters for Hydraulic and Static Structures, Earth Materials Laboratory Report No. EM-132, U. S. Bureau of Reclamation, 1947.

of these tests are given in table 2.

After the water passed through the model it was measured by means of calibrated orifices in the bottom of a cylindrical tank 14 inches in diameter and 20 inches deep. (See figure 2.) The orifices were round holes having sharp edges cut with a lathe in the center of circular brass disks. The disks were fitted into holes cut in the bottom of the tank in such a manner that the face of the disk was flush with the bottom of the tank. Four different sizes of orifices were provided to measure the range of discharges required for the tests. The diameters were 0.23, .34, .48 and .62 inches. One orifice was used at a time. Those not in use were shut off with rubber stoppers. With these orifices it was possible to measure the flows required for the tests. The head on the orifice was measured with a hook gage in a stilling well on the outside of the tank.

Although the flows to be measured were small, ranging from 0.321 to 5.14 gallons per minute, discharging this amount of water into the tank caused considerable turbulence. To reduce the turbulence, the water was discharged into a can 3 inches in diameter from which it overflowed on to a horizontal screen 8 inches above the orifices. This screen, which had 48 meshes to the inch, distributed the flow and cut down the velocity. Each orifice was calibrated by weighing the discharge in a definite time for several different heads. The results of the calibrations are shown in figure 6.

During the full scale tests of standard screens previously made, the head losses were measured for discharges of 0.0625, .125, .250, .500, .750 and 1.000 cubic foot per second per foot of screen. For the model, these discharges would have to be reduced in proportion to the scale ratio, if

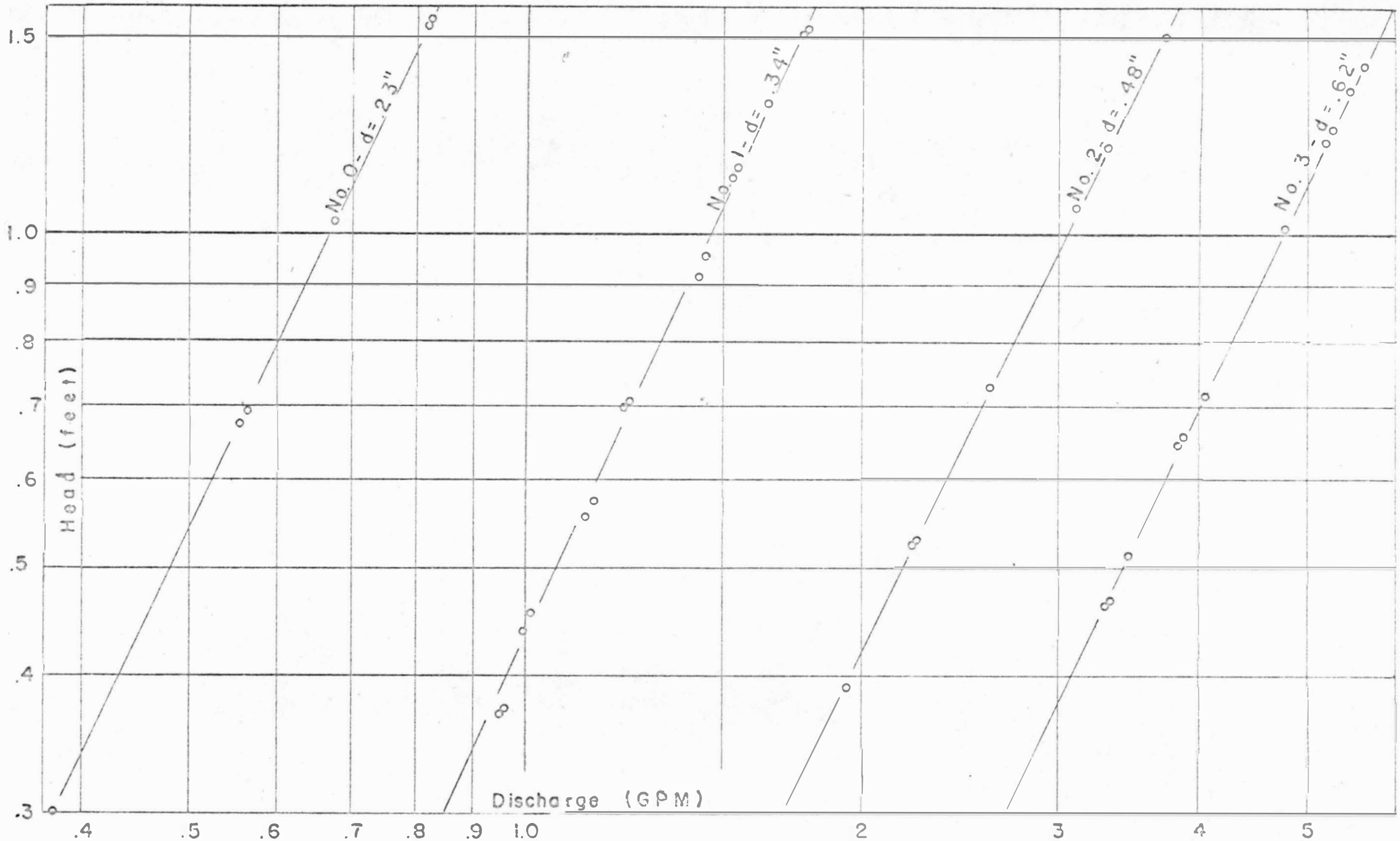

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Figure 6 .- Calibration curves for orifices.

the velocities were to be kept the same as for the full scale tests. The required discharges were first computed on the basis of the ratio of the area of the well screen in the model to the area of the screen in the prototype. However, it was decided that this method was in error because the critical area was the interface between the water-bearing formation and the gravel envelope. The flows actually tested in the model were based on the ratio of the area of the interface in the model to that in the prototype.

Method of Conducting Tests on Flow of Sand into Wells

In the study of the flow of sand into wells and the accompanying changes in the head losses, it was recognized that the degree of compaction of the gravel envelope and the water bearing formation might have considerable effect on the results obtained. For this reason a standard procedure was adopted for conducting the tests. It was hoped that the errors due to compaction of the material would be kept to a minimum by this method.

The plan adopted for conducting the tests was to measure the head losses in the sand and the gravel at the points indicated in figure 1 at the beginning and the end of each test. Each test lasted the same length of time. At the end of the test the gravel envelope was removed from the plastic tube and then washed to obtain the sand that had been carried into it from the aquifer. The sand that passed through the screen was also collected. The sand caught was then dried and screened to remove the rock powder formed during each test by handling the sand and gravel. Each screen was tested for suitable combinations of sand and gravel and for the range of discharges required to establish the pattern of the sand movement with increase in velocity of flow.

When getting ready to make a test, the plastic tube was set vertically on a plate having a plug that just fitted the inside of the tube. One of the wire mesh screens was then placed in position on the stops in the tube, after which the tube was filled with water. The sand chosen for the aquifer was then placed in the tube by hand, each handful being placed in contact with the material already in the tube so that there would be no tendency for the particles to segregate according to size. Sand was added until the column was about one inch higher than the final length required. The sand was compacted by tapping the tube 24 times with a plastic hammer. The taps were equally distributed along the axis of the tube on six lines 60 degrees apart. If at the end of 24 taps the sand column was too long or too short, sand was removed or added until the desired length of column was obtained. After the sand had been compacted another one of the mesh screens was placed in the tube on top of the sand and rotated until it was level.

The gravel was then placed in the tube in the same manner as the sand. It also was compacted by tapping the plastic tube, but only 18 taps were given to the tube. After bringing the gravel up to the desired length the surface was leveled by rotating a wooden disk on the gravel. This disk had radial grooves in the bottom to increase the effectiveness of the smoothing action. The disk was rotated by means of a handle attached to the center of the disk. Another disk about six inches above the grooved disk acted as a guide so that the final surface of the gravel would be at right angles to the axis of the tube.

After the surface had been leveled the well screen was placed on top of the gravel and pressed down until the gravel was in contact with all parts of the screen. The screen was held in place in this position by the collapsible sleeve which was pushed down against the screen.

While still in the vertical position the water was slowly drained from the model. After the water had drained out of the tube it was placed in the cradle in a horizontal position as shown in figure 2. The end plates were then attached and drawn tight by means of the wing nuts on the tie rods. The approximate quantity of water required for the test was turned into the model and at the same time the downstream end of the tube was raised 6 inches so that air in the sand and gravel would be forced to the top as the water rose. (See figure 7.) While the model was being filled, air vents along the top of the tube were kept open.

After all the air visible in the tube had escaped the air vents were closed and the tube was lowered to the horizontal position. The piezometers along the side of the tube were then opened one at a time and allowed to discharge until all the entrapped air had escaped. As soon as the flow became uniform the piezometer was connected to the proper glass tube on the manometer board. When all the piezometer connections had been made, the levels in the manometers were checked to see whether there was air trapped in any of the rubber tubes. This could be easily determined because the glass tubes on the manometer board were arranged in the same order as the piezometers and consequently any radical change in the difference between levels in adjacent tubes was immediately apparent. Disconnecting the rubber tube at the piezometer and allowing the water to flow out of the manometer took care of this problem.

When all the manometers were working properly, the flow through the model was adjusted by regulating the valves on the inlet and outlet pipes until the correct head was indicated by the hook gage in the orifice tank

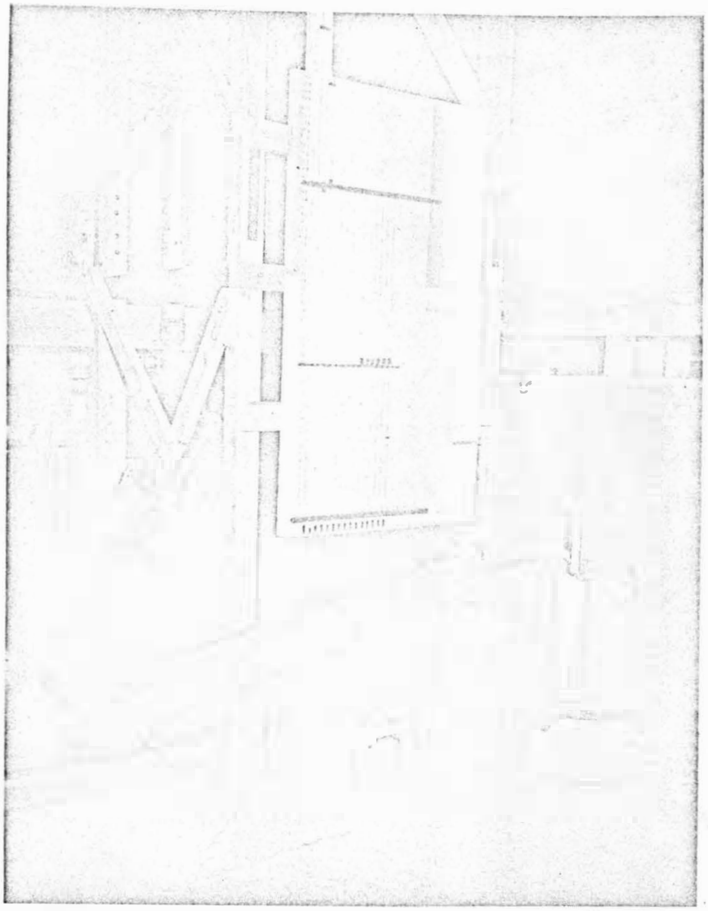

Figure 7.-- Model tilted so that entrapped air can escape at high point of plastic tube.

for the desired discharge and the orifice in use at the time. This adjustment was made as quickly as possible because variations in the rate of flow would affect the amount of sand movement.

In the preliminary tests, when stable flow at the desired rate had been established, and after the elapse of 30 minutes from the time water was turned into the model, all the rubber tubes leading to the manometers were shut off at once by means of a clamp that extended across all the tubes. This arrangement made it possible to get simultaneous readings of the heads at all piezometers. As soon as the readings had been taken and recorded the clamp was released. A second set of readings was taken in the same manner 30 minutes later.

The original plan was to run each test for one hour but it was observed that practically all the sand movement occurred in the first 30 minutes. For this reason all except the preliminary tests were for a 30-minute period. Furthermore, the preliminary tests showed that the heads registered by the piezometers did not hold constant. As the sand moved into the gravel envelope the total head loss at first increased and then after most of the sand movement had stopped the head loss gradually decreased. Because the initial reading of the head loss was affected by the time required to adjust the flow, these readings were discontinued and for most of the tests the readings at the end of the test only were taken. It is believed that the head losses measured at this time are a measure of the losses that would occur in a well under similar conditions.

After the manometer readings at the end of the test had been taken and recorded, the inlet valve was closed and an air vent on the top of the model opened. This permitted the water to discharge slowly through the outlet hose. When the water had drained down to the level of the outlet connection, the end plates and also the collapsible sleeve and the well screen were removed. Sand that had passed through the gravel envelope and was caught in the chamber at the end of the tube was collected. The gravel envelope was then removed, care being taken to recover all the sand. After the gravel had been removed the sand was dumped out and saved for reuse later. However all material that was screened out of the gravel was returned to the sand so that the characteristics of the material would not change during the testing program.

The sand was removed from the gravel by screening and washing. In each case a screen of appropriate size for the gravel being tested was used in separating the sand from the gravel. The wash water and sand were caught in a tub from which the sand was later recovered and dried. The sand that went through the gravel envelope and was caught in the space at the end of the tube was added to the material washed out of the gravel envelope. After the sand had been dried it was screened to remove the material finer than the original sand. This fine material which resulted from the handling of the sand and gravel consisted of rock powder. Since the weight of this fine material was small the total weight of sand was used as the basis for comparing the amount moved at each velocity.

A complete record of each test was kept on forms prepared for the purpose. The record consisted of the type and size of perforations of the screen, the size of sand in the aquifer and gravel in the envelope, the manometer readings, the size of orifice and the gage height, the temperature of the water after it had passed through the model, and the weight of the sand moved.

Results of Tests of Flow of Sand into Wells

The results of all the tests on the flow of sand are given in table 3. The data were assembled according to the various combinations of gravel envelopes and sands, and the tests on all the screens with a particular sand and gravel combination are shown together. This arrangement of the data made it possible to compare the effect of the different screens on the flow of sand. The amount of sand moved for the progressively increasing discharges is also shown for each screen together with the actual velocity through the sand during the test, that is, the velocity through the intersticies between the sand particles.

Analysis of these data indicates that the amount of sand moved into the gravel envelope increased with the velocity. At low velocities this is not always true, but for these velocities the amount moved was so small that the unavoidable inaccuracies in the work overshadowed the effect of the increase in velocity. However, at higher velocities the increase in sand movement with increase in velocity is readily apparent. It is also apparent that the amount of sand of a given size increases if the size of the gravel in the gravel envelope is increased. It was originally thought that the amount of sand movement would not be greatly affected until a critical velocity was reached, but this is not shown by the data in the table. If there was a critical velocity it was not apparent from the tests. However, such a point might have been found, had observations been made at more velocities in the critical range. For the tests reported each succeeding velocity was double the previous one. This distribution gives uniform intervals on a log plot but it was probably too great for this problem. Because of the time required to make the tests, the number had to be limited. This method

Table 3.-- Summary of Results of all tests of flow of sand into wells. (Actual velocity through sand in model in feet per second times 10^{-2} and amount of sand moved in grams dry weight. Duplicate readings are marked with an asterick).

Gravel Size	Sand Size Screen No.	Well Screen Type	Well Screen Slot Width	Equivalent flow in prototype in cubic feet per second: 0.0625 Vel.	0.0625 Sand	0.125 Vel.	0.125 Sand	0.250 Vel.	0.250 Sand	< 0.500 Vel.	< 0.500 Sand	0.500 Vel.	0.500 Sand	< 1.00 Vel.	< 1.00 Sand	1.00 Vel.	1.00 Sand
Inch			Inch														
1/16	20-30	C-c	0.100	--	--	--	--	3.76	0.0	--	--	7.45	3.0	--	--	14.9	1.8
1/16	30-40	C-c	.100	--	--	1.92	1.5	3.82	1.1	6.27	1.1	--	--	--	--	--	--
1/16	40-60	C-c	.100	1.23	0.8	1.99	1.9	3.02	1.1	--	--	--	--	--	--	--	--
1/16	40-60	C-b	.040	1.23	2.5	1.98	1.7	--	--	--	--	7.97	2.5	--	--	--	--
1/16	40-60	C-a	.020	1.23	1.1	1.99	1.1	3.10	1.9	--	--	7.97	2.4	--	--	--	--
1/16	40-60	B-a	1/16	1.23	1.0	1.99	1.0	2.89	1.3	--	--	7.97	2.8	--	--	--	--
1/16	40-60	D-a	1/16	--	--	1.99	1.9	--	--	--	--	7.92	2.5	--	--	--	--
1/8	20-30	C-b	.040	--	--	--	--	3.71	1.7	--	--	7.70	1.2	13.9	2.3	--	--
1/8	30-40	C-c	.100	--	--	1.92	1.5	3.82	2.1	5.80	4.1	--	--	--	--	15.3	11.0
1/8	30-40	C-b	.040	--	--	1.92	2.1	3.86	4.0	6.21 5.81	7.9* 3.2	--	--	--	--	15.3	16.4
1/8	30-40	C-a	.020	--	--	1.93	2.1	3.82	3.3	6.95 5.79	8.8* 5.4	--	--	--	--	15.3	15.7
1/8	30-40	B-b	1/8	--	--	1.90	1.4	3.82	3.1	5.51	3.6	--	--	--	--	15.3	15.2
1/8	30-40	B-a	1/16	--	--	1.90	4.0	3.82	5.6	5.83 5.79	7.0* 4.5	--	--	--	--	15.2	16.5
1/8	30-40	D-b	1/8	--	--	--	--	3.80	4.1	--	--	7.64	8.4	--	--	15.2	15.7
1/8	30-40	D-a	1/16	--	--	--	--	3.83	4.5	--	--	7.64	8.2	--	--	15.2	14.5
1/8	40-60	C-c	.100	.99	3.4	1.98	5.5	2.99	10.7	--	--	7.97	68.7	--	--	--	--
1/8	40-60	C-b	.040	1.08	6.8	1.99	7.3	3.42	15.7	--	--	7.97	42.5	--	--	--	--

Table 3.-- Summary of Results of all tests of flow of sand into wells. (Continued)

Gravel Size Inch	Sand Size Screen No.	Well Screen Type	Well Screen Slot Width Inch	0.0625 Vel.	0.0625 Sand	0.125 Vel.	0.125 Sand	0.250 Vel.	0.250 Sand	< 0.500 Vel.	< 0.500 Sand	0.500 Vel.	0.500 Sand	< 1.00 Vel.	< 1.00 Sand	1.00 Vel.	1.00 Sand
1/8	40-60	C-a	.020	.99	5.3	1.96	11.2	2.99	16.0	--	--	7.97	39.5	--	--	--	--
1/4	10-14	C-c	.100	--	--	--	--	3.78	0.4	--	--	7.54	0.4	--	--	15.1	1.0
1/4	14-20	C-d	.200	--	--	--	--	3.70	1.5	--	--	7.39	2.7	--	--	15.2	4.2
1/4	20-30	C-d	.200	--	--	1.86	1.8	3.70	3.5	--	--	7.44	10.4	12.3	23.4	14.9	55.8
1/4	20-30	C-c	.100	1.07	2.3	1.85 1.87	8.0* 3.5	3.73	5.5	--	--	7.65	7.6	--	--	15.1 14.9	23.5* 59.8
1/4	20-30	C-b	.040	--	--	1.86	2.1	3.73	6.4	--	--	7.51	17.2	12.5	25.4	14.9	49.9
1/4	20-30	B-c	3/16	--	--	1.85	2.4	3.73	4.0	--	--	7.44	14.2	11.8	30.0*	14.8	55.0
1/4	20-30	B-b	1/8	--	--	1.86	2.7	3.76	5.3	--	--	7.65	16.7	12.2	25.0	14.9	55.4
1/4	20-30	D-c	3/16	--	--	--	--	3.73	4.5	--	--	7.44	14.3	--	--	15.0	65.9
1/4	20-30	D-b	1/8	--	--	--	--	3.73	4.6	--	--	7.44	22.3*	--	--	15.0	66.6
1/4	30-40	C-d	.200	1.19	24.8	1.92	41.1	3.82	82.8	6.06	152.6	--	--	--	--	--	--
1/4	30-40	C-c	.100	--	--	1.91 1.92	32.3* 26.1	3.82	70.0	7.16 6.06	293.0* 142.8	--	--	--	--	--	--
1/4	30-40	C-b	.040	1.19	27.9	1.93	33.2	3.83	80.8	6.39 6.06	170.6* 124.7	--	--	--	--	--	--
1/4	40-60	C-a	.020	Wash out		--	--	--	--	--	--	--	--	--	--	--	--
1/2	10-14	C-d	.200	--	--	--	--	3.74	0.5	--	--	7.50	0.5	--	--	15.1	1.4*
1/2	14-20	C-d	.200	--	--	--	--	3.69	1.4	--	--	7.41	1.6	--	--	14.9 14.8	13.5 6.1
1/2	14-20	C-c	.100	--	--	--	--	3.7	1.5	--	--	7.38	1.7	--	--	15.0	6.9
1/2	14-20	B-c	3/16	--	--	--	--	3.78	1.8	--	--	7.33	3.4*	--	--	14.8 14.8	16.5* 6.3
1/2	14-20	D-c	3/16	--	--	--	--	3.78	1.6	--	--	7.38	5.5	--	--	14.9	10.7
1/2	20-30	C-b	#40	--	--	1.85	50.0	Wash out		--	--	--	--	--	--	--	--

of increasing the velocities did however provide a plan for covering a wide range of velocities as there was no way of knowing in advance what range of velocities should be investigated.

Of particular interest in table 3 is the fact that neither the type of screen nor the size of perforations had any conspicuous effect on the amount of sand that was carried from the water bearing formation into the gravel envelope. This is no doubt partly due to the fact that appropriate sizes of perforations were chosen for each size of gravel tested regardless of the type of screen. In order to bring this out more clearly, the results of the tests on all the screens regardless of type or size of openings with the same sand and gravel combinations were averaged and then plotted on semi-logarithmic paper. The results are shown in table 4 and figures 8 to 12. These figures show how the amount of sand moved increases with the velocity for each sand and gravel combination and also how it increases as the sand gets finer for each gravel size in the envelope.

The average amount of sand moved at each velocity was computed also for each sand and gravel combination for each type of screen without regard to the size of perforations. The results are given in table 5. They are shown plotted in figures 13 to 15. These plots all show the increase in the amount of sand moved as the velocity increased. The plots show also that the curve for each sand and gravel combination is in approximately the same position in each of the figures. This is readily seen because the symbols used for identical sand and gravel combinations are the same on each figure. The fact that these curves are in the same position indicates that the type of screen had very little effect on the amount of sand that moved into the gravel envelope. It should be noted however, that for the higher velocities

Table 4.-- Average of the results of the tests of flow of sand for all screens with the same sand and gravel combination and the same discharge. (Velocity in feet per second times 10^{-2}).

Gravel Size	Sand Size	Diameter Ratio Gravel / Sand	No. of Tests	Equivalent flow in prototype in cubic feet per second													
				0.0625		0.125		0.250		< 0.500		0.500		<1.00		1.00	
				Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand
Inch	Screen No.			Ft/sec	Grams	Ft/sec	Grams	Ft/sec	Grams	Ft/sec	Grams	Ft/sec	Grams	Ft/sec	Grams	Ft/sec	Grams
1/4	10-14	3.7	1	--	--	--	--	3.78	0.4	--	--	7.54	0.4	--	--	15.1	1.0
1/2	10-14	8.4	1	--	--	--	--	3.74	0.5	--	--	7.50	0.5	--	--	15.1	1.4
1/4	14-20	5.5	1	--	--	--	--	3.70	1.5	--	--	7.39	2.7	--	--	15.2	4.2
1/2	14-20	12.5	4	--	--	--	--	3.70	1.6	--	--	7.37	3.0	--	--	14.9	10.0
1/8	20-30	4.4	1	--	--	--	--	3.71	1.7	--	--	7.70	1.2	13.9	2.3	--	--
1/4	20-30	8.4	7	1.07	2.3	1.86	3.4	3.73	4.8	--	--	7.51	14.7	12.2	26.0	15.0	54.0
1/2	20-30	18.6	1	--	--	1.85	50.0	wash out		--	--	--	--	--	--	--	--
1/16	30-40	3.5	1	--	--	1.92	1.5	3.82	1.1	6.27	1.1	--	--	--	--	--	--
1/8	30-40	7.1	7	--	--	1.91	2.2	3.82	3.8	6.00	5.6	--	--	--	--	15.3	15.0
1/4	30-40	13.1	4	1.19	26.3	1.92	33.2	3.82	77.8	6.35	176.7	--	--	--	--	--	--
1/16	40-60	5.4	4	1.23	1.3	1.93	1.5	3.00	1.4	--	--	7.97	2.6	--	--	--	--
1/8	40-60	10.7	3	1.02	5.2	1.98	8.0	3.13	14.1	--	--	7.97	50.2	--	--	--	--
1/4	40-60	19.8	1	0.9	267.6	--	--	--	--	--	--	--	--	--	--	--	--

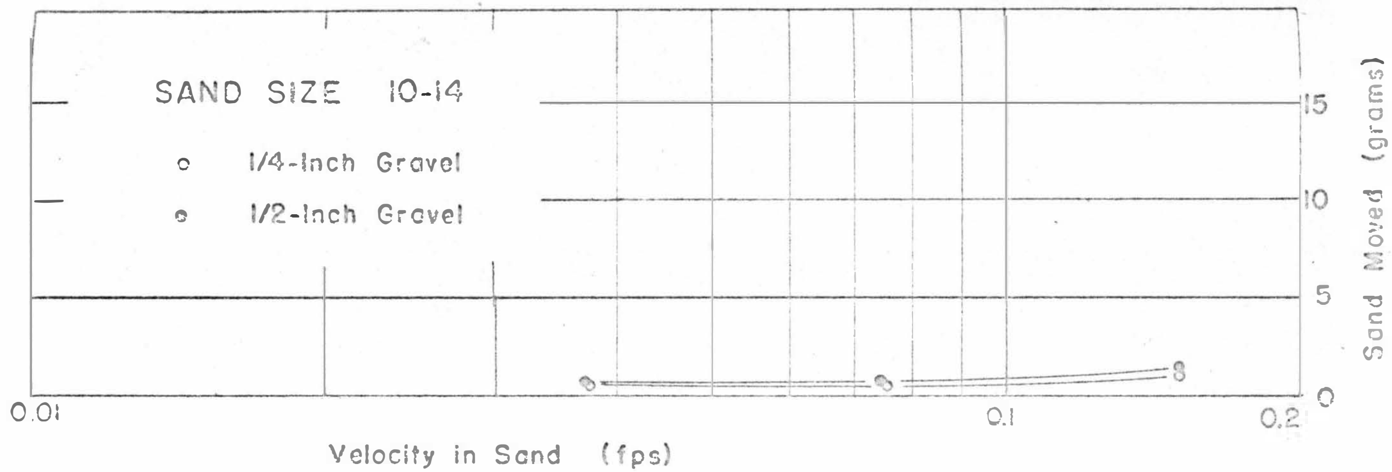

Figure 8 .-Amount of sand moved into gravel envelope at different velocities.

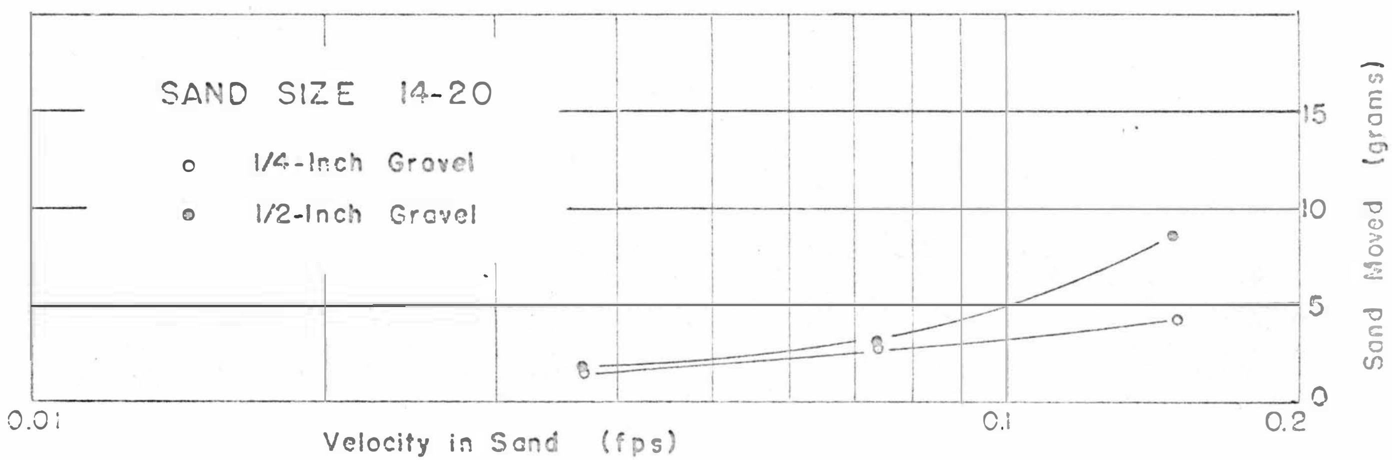

Figure 9 .-Amount of sand moved into gravel envelope at different velocities.

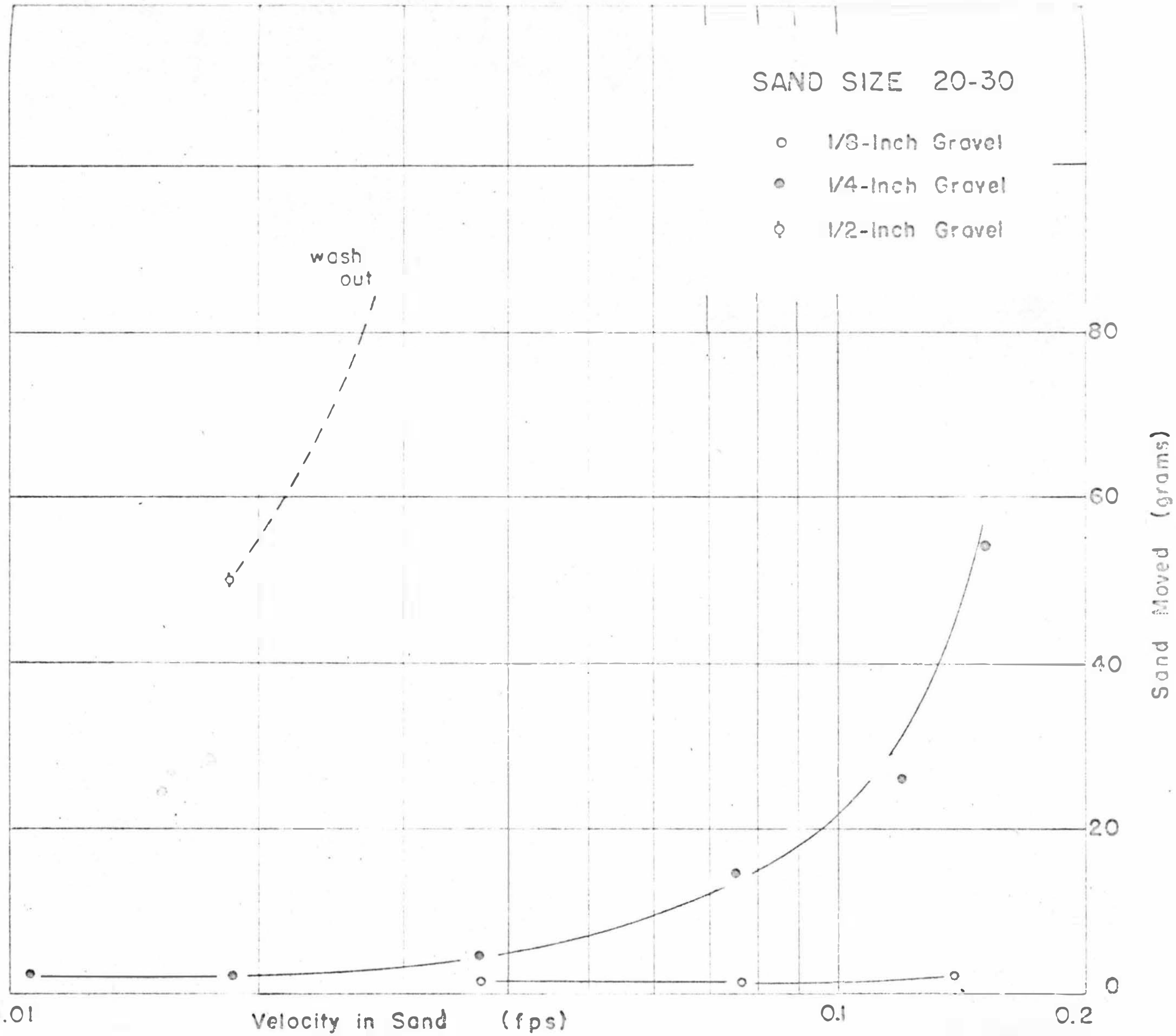

Figure 10.-Amount of sand moved into gravel envelope at different velocities.

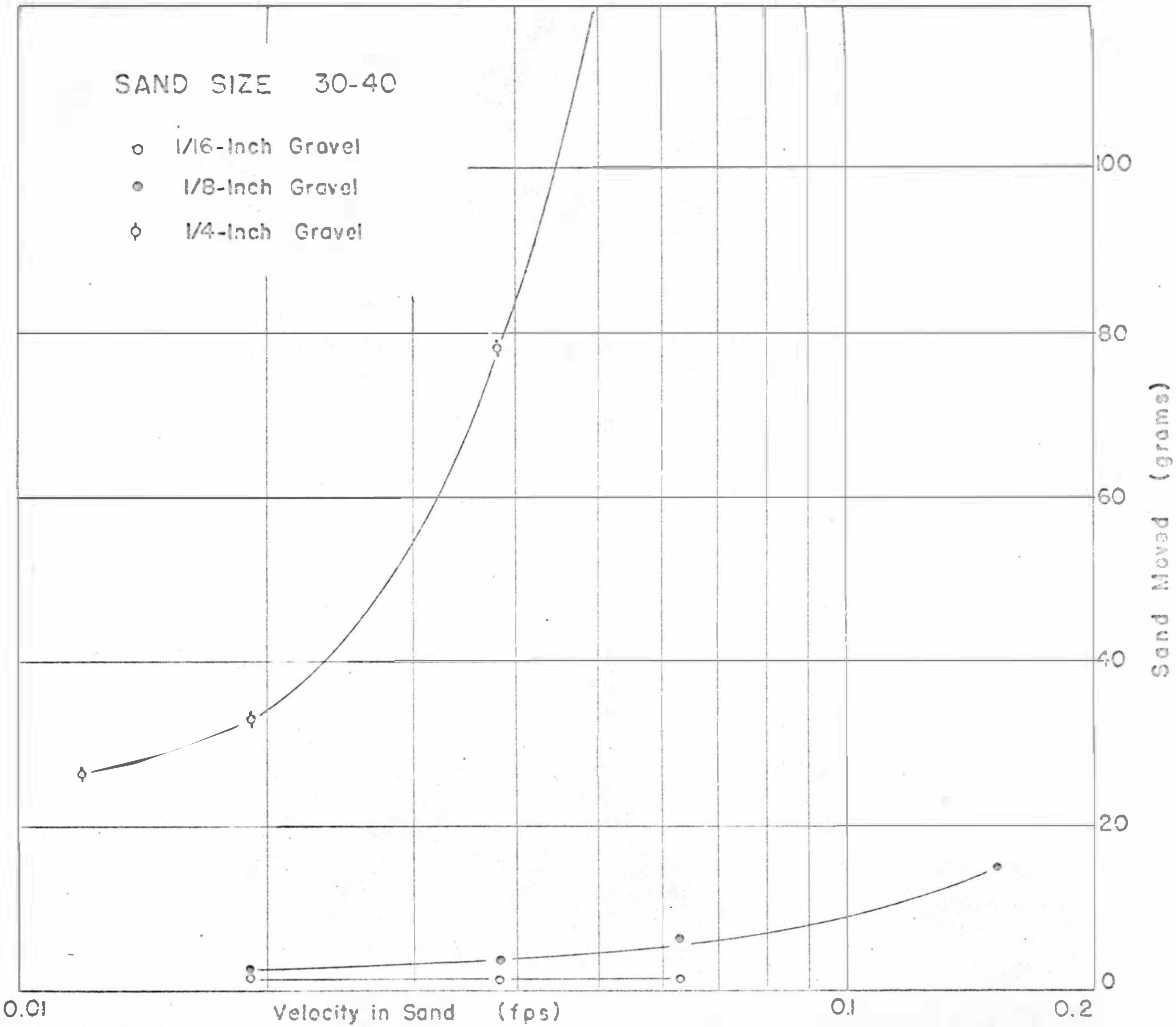

Figure 11 .-Amount of sand moved into gravel envelope at different velocities.

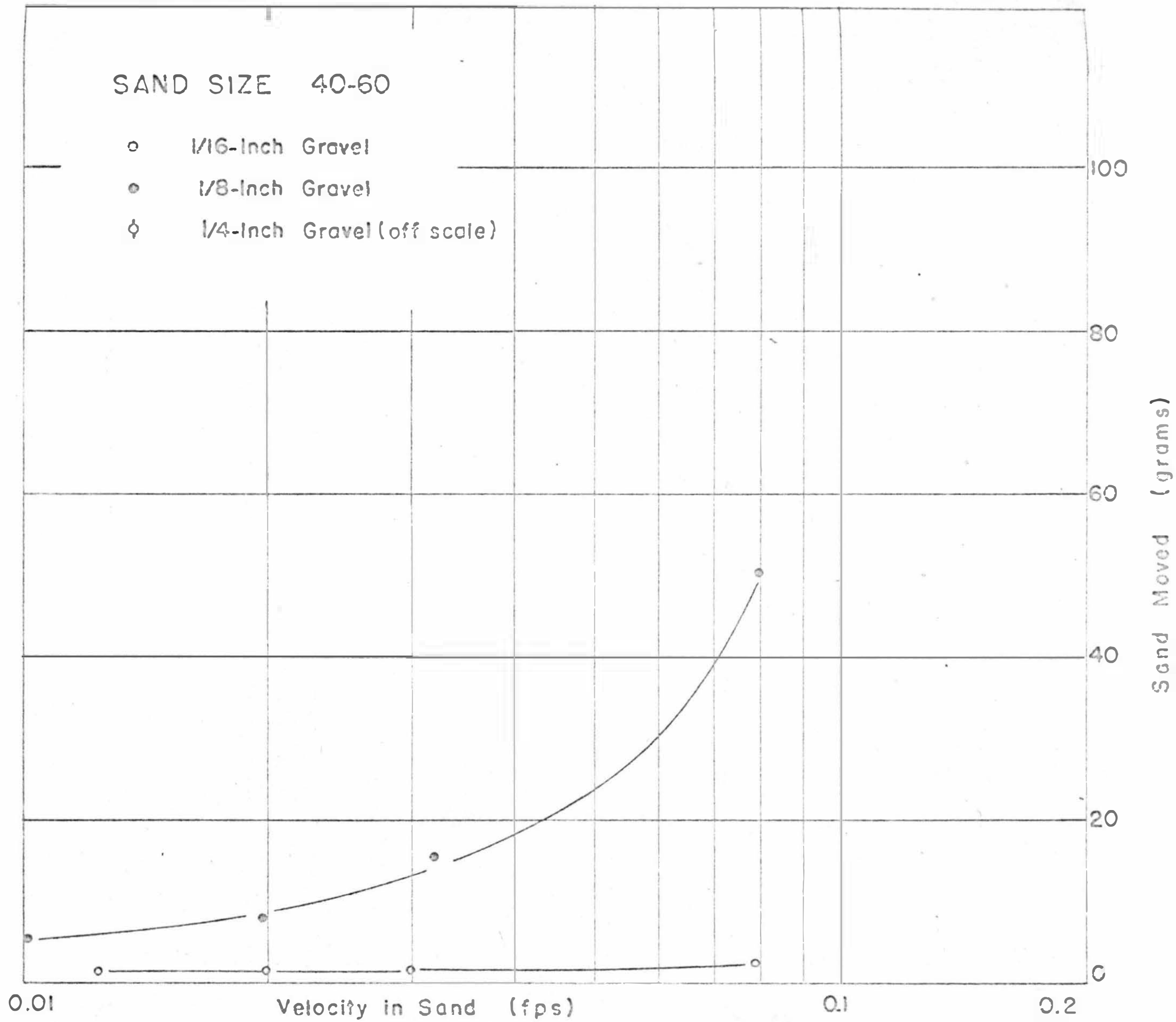

Figure 12 .-Amount of sand moved into gravel envelope at different velocities.

Table 5.-- Average of the results of the tests of the flow of sand for all screens of the same type with the same sand and gravel combination and the same discharge.

Gravel Size	Sand Size	Screen		Equivalent flow in prototype in cubic feet per second										
		Type	Width of Openings	0.0625		0.125		0.250		< 0.500		0.500		<
				Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.	Sand	Vel.
Inch	Screen No.		Inch	Ft/sec	grams	Ft/sec	grams	Ft/sec	grams	Ft/sec	grams	Ft/sec	grams	Ft/se
1/16	40-60	C	.10, .04, .02	1.23	1.5	1.99	1.6	3.1	1.5	--	--	8.0	2.5	--
1/16	40-60	B	1/16	1.23	1.0	1.99	1.0	2.9	1.3	--	--	8.0	2.8	--
1/16	40-60	D	1/16	--	--	1.99	1.9	--	--	--	--	7.9	2.5	--
1/8	30-40	C	.10, .04, .02	--	--	1.90	1.9	3.8	3.1	6.1	5.9	--	--	--
1/8	30-40	B	1/8, 1/16	--	--	1.90	2.7	3.8	4.4	5.7	5.0	--	--	--
1/8	30-40	D	1/8, 1/16	--	--	--	--	3.8	4.3	--	--	7.6	8.3	--
1/8	40-60	C	.10, .04, .02	1.02	5.2	1.98	8.0	3.2	14.1	--	--	7.9	50.2	--
1/4	20-30	C	.20, .10, .04	1.07	2.3	1.86	3.8	3.7	5.1	--	--	7.5	11.7	12.4
1/4	20-30	B	3/16, 1/8	--	--	1.86	2.6	3.7	4.7	--	--	7.5	15.4	12.[illegible]
1/4	20-30	D	3/16, 1/8	--	--	--	--	3.7	4.5	--	--	7.4	18.3	--
1/4	30-40	C	.20, .10, .02	1.19	26.3	1.92	33.2	3.8	77.8	6.3	176.7	--	--	--
1/2	14-20	C	.20, .10	--	--	--	--	3.7	1.4	--	--	7.4	1.6	--
1/2	14-20	B	3/16	--	--	--	--	3.7	1.8	--	--	7.3	3.4	--
1/2	14-20	D	3/16	--	--	--	--	3.7	1.6	--	--	7.4	5.5	--

[illegible] of the [illegible] of the flow of sand for all screens [illegible] with the same sand and gravel combination and the same discharge.

	Equivalent flow in prototype in cubic feet per second													
	0.0625		0.125		0.250		< 0.500		0.500		< 1.00		1.00	
	Vel. Ft/sec	Sand grams	Vol. Ft/sec	Sand grams	Vel. Ft/sec	Sand grams	Vel. Ft/sec	Sand grams	Vel. Ft/sec	Sand grams	Vel. Ft/sec	Sand grams	Vel. Ft/sec	Sand grams
2	1.23	1.5	1.99	1.6	3.1	1.5	--	--	8.0	2.5	--	--	--	--
	1.23	1.0	1.99	1.0	2.9	1.3	--	--	8.0	2.8	--	--	--	--
	--	--	1.99	1.9	--	--	--	--	7.9	2.5	--	--	--	--
[illegible]	--	--	1.90	1.9	3.8	3.1	6.1	5.9	--	--	--	--	15.3	14.4
	--	--	1.90	2.7	3.8	4.4	5.7	5.0	--	--	--	--	15.3	15.8
	--	--	--	--	3.8	4.3	--	--	7.6	8.3	--	--	15.2	15.1
[illegible]	1.02	5.2	1.98	8.0	3.2	14.1	--	--	7.9	50.2	--	--	--	--
[illegible]	1.07	2.3	1.86	5.8	3.7	5.1	--	--	7.5	11.7	12.4	24.4	14.9	47.2
	--	--	1.86	2.6	3.7	4.7	--	--	7.5	15.4	12.0	27.5	14.9	55.2
	--	--	--	--	3.7	4.5	--	--	7.4	18.3	--	--	15.0	66.6
	1.19	26.3	1.92	33.2	3.8	77.8	6.3	176.7	--	--	--	--	--	--
	--	--	--	--	3.7	1.4	--	--	7.4	1.6	--	--	14.9	8.8
	--	--	--	--	3.7	1.8	--	--	7.3	3.4	--	--	14.8	11.4
	--	--	--	--	3.7	1.6	--	--	7.4	5.5	--	--	14.9	10.7

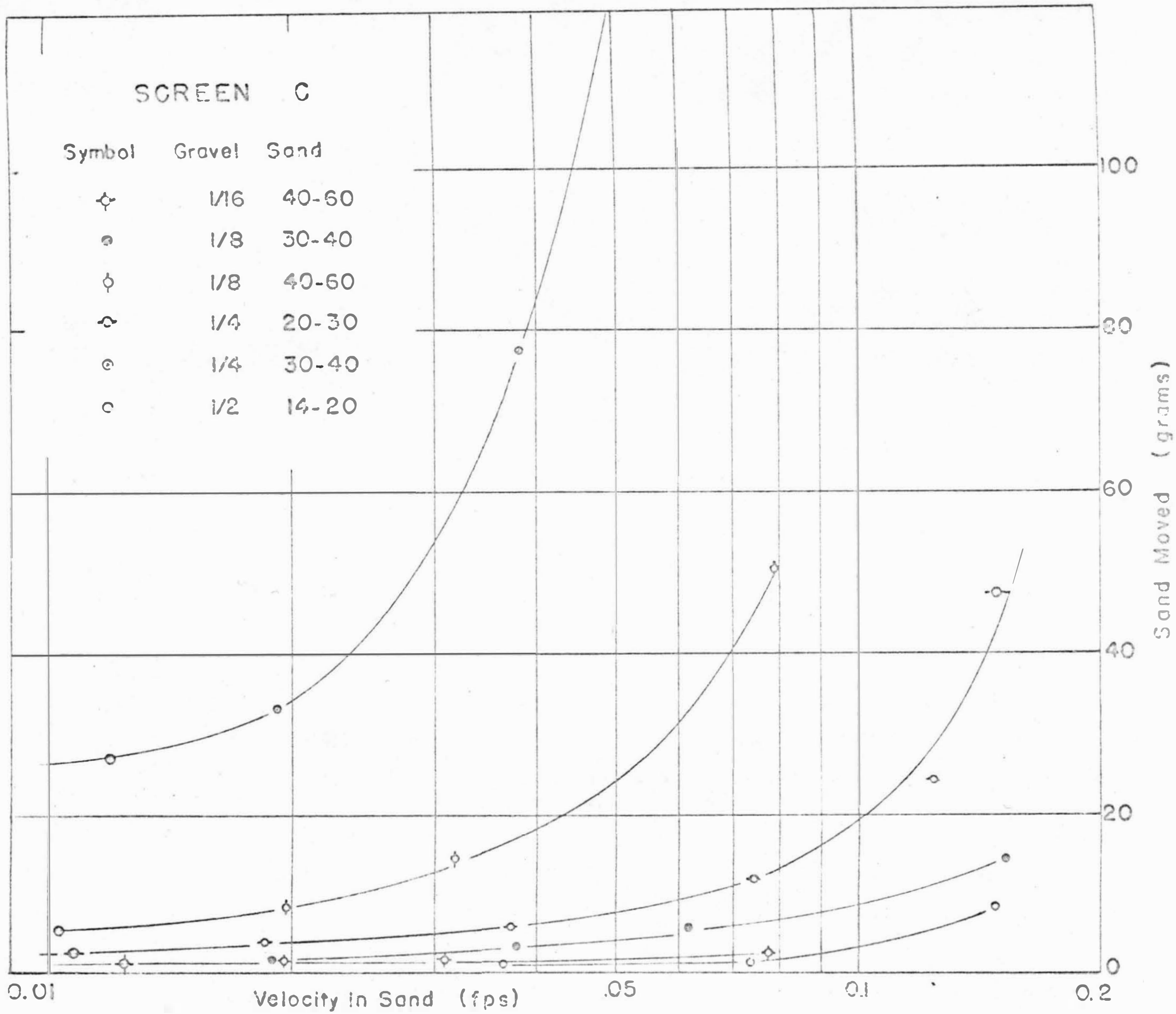

Figure 13 .-Average amount of sand moved into gravel envelopes with C-type screens at different velocities.

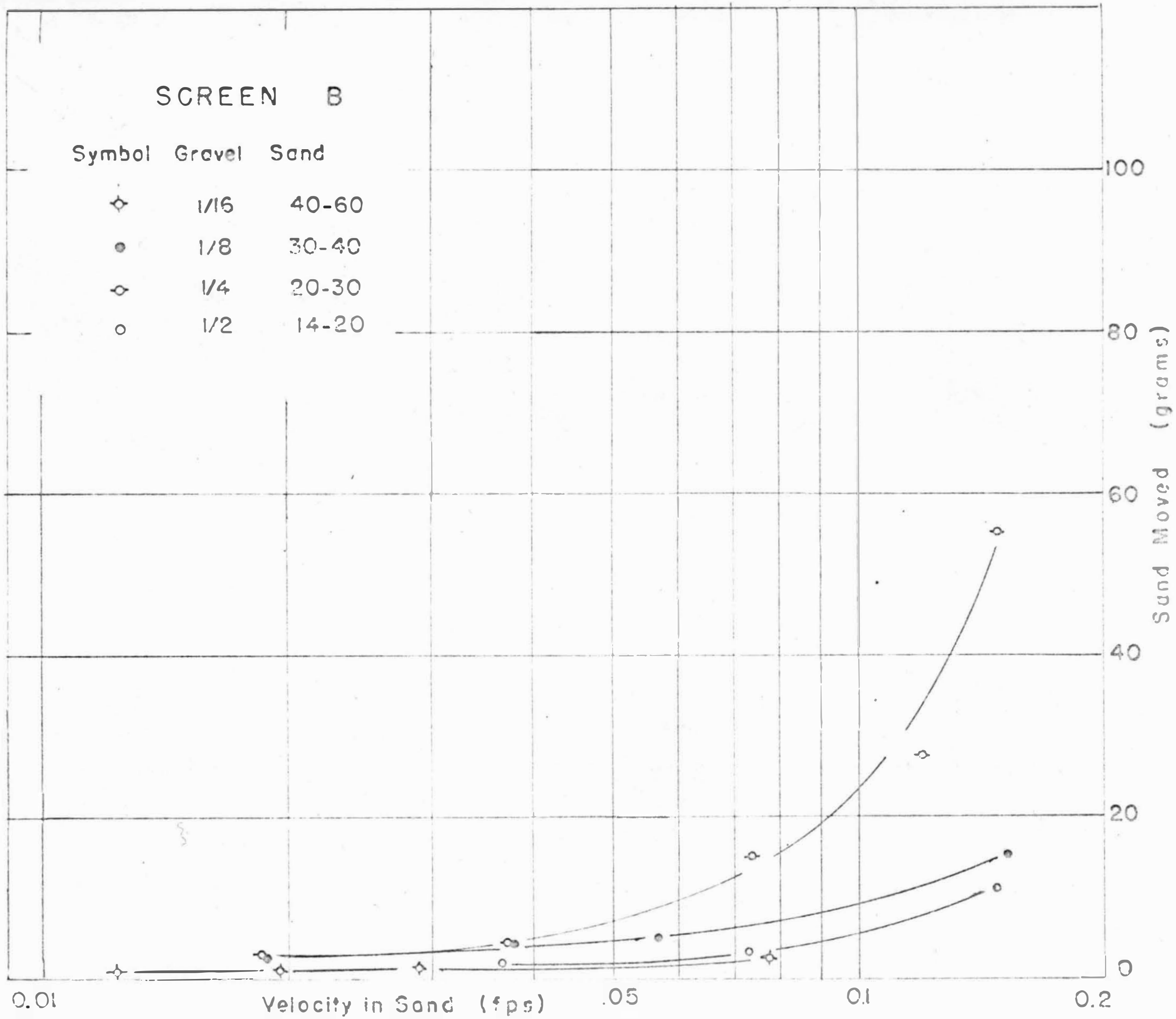

Figure 14 .-Average amount of sand moved into gravel envelopes with B-type screens at different velocities.

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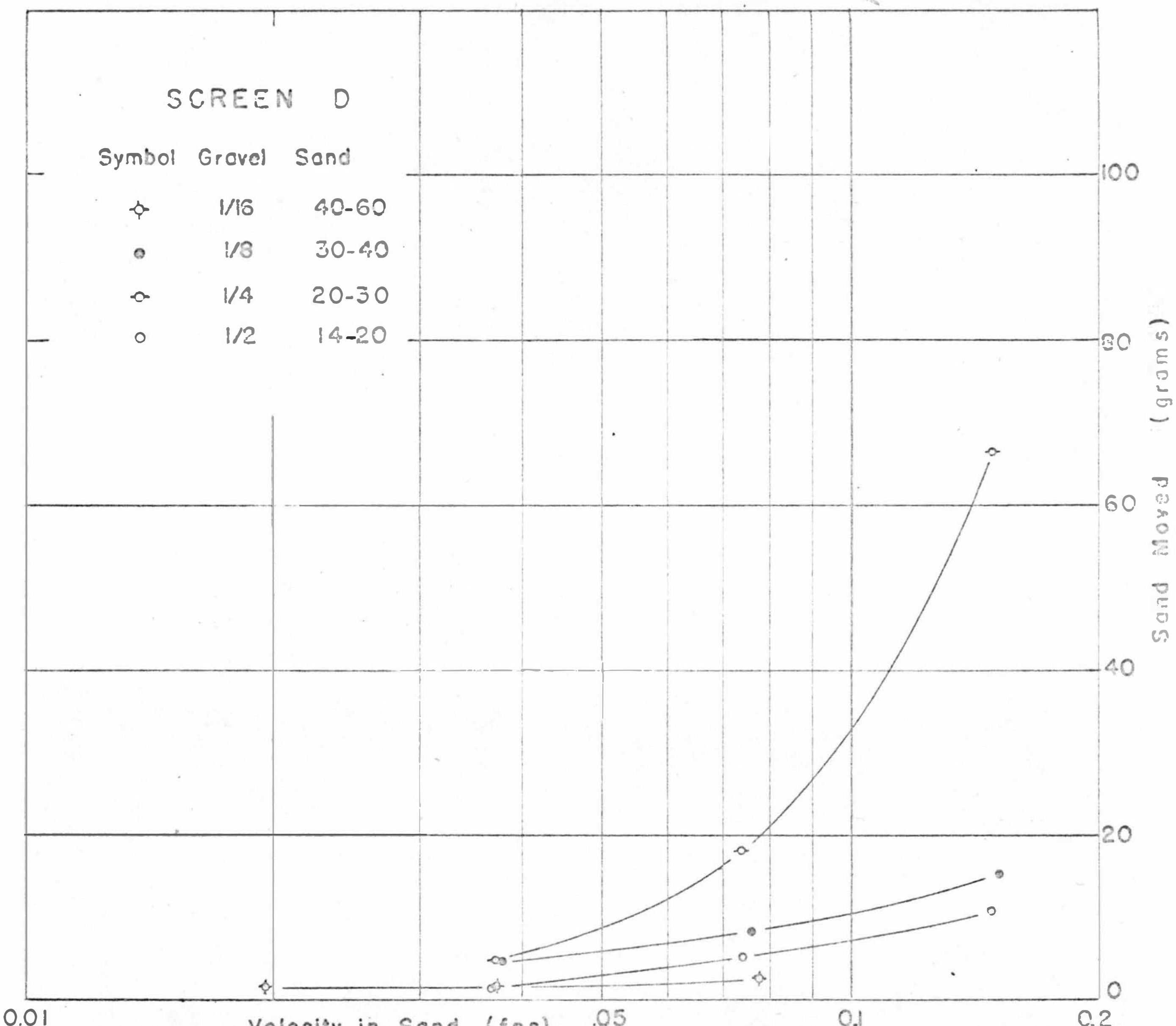

Figure 15 .-Average amount of sand moved into gravel envelopes with D-type screens at different velocities.

when the finest sand was used, more sand was moved in the tests on the type B and type D screens than in the tests on the type C screens. Since the type B and type D screens have smaller percentages of openings than the type C screens, the velocities through the openings are higher and consequently the carrying power of the water is greater.

Loss of Head in Sand and Gravel

The results of the loss of head readings on the piezometers attached to the model at different points along the side of the plastic tube (figure 1) used for the model studies are given in table 6. All the tests on each screen for the various combinations of sand and gravel are shown together. For each sand and gravel combination the results are arranged in the order of increasing velocities. By this arrangement it is possible to see how the head loss increases with the velocity for each combination of screen, sand and gravel.

All the losses were measured between the piezometer (No. 1) in the chamber at the downstream end of the tube and the piezometer indicated by the number at the head of the column in the table. The losses were obtained by subtracting the manometer reading for Piezometer No. 1, from the manometer reading for the piezometer number under which the loss is recorded. All losses are in inches.

As previously explained the manometer readings were taken at the end of each test. In order to get simultaneous readings all the manometers were shut off at once by means of a clamp which extended across the rubber tubes leading to the manometers. Although this method made it possible to get simultaneous readings of the heads it did not eliminate the possibility of inconsistencies in the readings. This is particularly noticeable in the

Table 6.-- Loss of head through sand and gravel in model study of flow of sand into wells for various combinations of screen, sand and gravel.
(Loss of head measured between piezometer indicated and piezometer No. 1 (See figure).

Size				Piezometer Number											
Gravel	Sand	Velocity in sand	Sand Moved	2	3	4	5	6	7	8	9	10	13	14	15
in.	Screen No.	ft/sec	grams	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Type C-a screen with 0.020-inch slots															
1/16	40-60	0.0123	1.1	45.9	26.98	13.64	7.30	5.61	3.75	1.96	--	1.12	0.89	0.47	-0.01
		.0199	1.1	71.0	40.56	20.45	11.06	8.52	5.86	3.46	1.59	1.52	1.18	.50	- .23
		.031	1.9	103.1	62.1	32.04	18.05	14.45	10.46	6.36	--	2.97	2.41	1.36	.23
		.0797	2.4	283.4	161.0	86.3	48.9	--	27.9	18.1	11.0	10.6	8.69	4.67	.43
1/8	30-40	.0193	2.1	37.8	24.06	13.56	7.19	5.46	3.46	1.46	.35	--	.27	.15	- .03
		.0382	3.3	59.4	33.23	14.55	4.86	2.05	1.01	.98	--	.93	.75	.42	.06
		.0579	5.4	89.4	51.26	24.58	10.96	7.30	3.03	1.86	--	--	--	--	--
		.0695	8.8	103.7	60.95	28.34	11.66	8.32	4.36	2.22	--	1.97	1.61	.96	.07
1/8	40-60	.0099	5.3	34.6	19.10	8.65	3.70	2.37	.84	.22	--	.17	.14	.05	- .05
		.0196	11.2	72.1	38.96	17.45	7.13	4.37	1.72	.36	--	.26	.16	.01	- .22
		.0299	16.0	104.1	57.59	27.69	13.51	9.50	5.21	2.69	--	.63	.49	.21	- .04
		.0797	39.5	311.3	190.3	97.5	55.5	--	33.0	23.6	12.0	3.30	2.29	1.22	- .03
Type C-b screen with 0.040-inch slots															
1/16	40-60	.0123	2.5	41.6	23.16	11.30	5.54	4.02	2.18	1.13	--	1.04	.83	.42	.01
		.0198	1.7	63.2	35.42	17.73	9.29	6.96	4.42	1.90	--	1.71	1.33	.71	.01
		.0797	2.5	303.2	181.7	99.6	58.2	47.3	35.5	23.3	14.17	13.69	11.11	6.03	.69
1/8	20-30	.0371	1.7	21.20	13.07	6.68	3.08	1.99	1.20	.87	--	.78	.63	.31	- .06
		.077	1.2	47.0	28.27	14.61	7.56	5.71	3.63	2.54	--	2.31	1.91	1.04	.12
		.139	2.3	87.8	--	--	--	--	--	--	--	--	4.35	2.44	.36
1/8	30-40	.0192	2.1	32.2	17.86	7.95	3.06	1.69	.49	.43	--	.38	.28	.10	- .05
		.0336	4.0	67.4	39.8	20.62	11.23	8.61	5.96	3.25	--	.81	.61	.18	- .18
		.0581	3.2	102.9	57.87	29.48	15.85	12.31	8.61	5.18	1.89	1.70	1.36	.73	- .03
		.0621	7.9	99.8	61.36	31.26	17.17	13.52	9.47	5.93	--	2.06	1.59	.88	.16
1/8	40-60	.0108	6.8	36.3	20.36	9.40	4.11	2.74	1.05	.27	--	.26	.19	.17	- .05
		.0199	7.3	64.7	36.78	17.66	9.18	6.73	4.14	2.19	.62	.45	.36	.20	- .01
		.0342	15.7	103.1	55.40	24.69	9.90	5.81	2.93	1.36	--	.72	.58	.29	- .07
		.0797	42.5	313.2	177.7	90.9	48.9	38.1	26.8	17.75	7.83	3.33	2.43	1.39	.15

Table 6 .-- Loss of head through sand and gravel in model study of flow of sand into wells for various combinations of screen, sand and gravel. (Continued)
(Loss of head measured between piezometer indicated and piezometer No. 1 (see figure).

Size		Velocity in sand	Sand Moved	Piezometer Number											
Gravel	Sand			2	3	4	5	6	7	8	9	10	13	14	15
in.	Screen No.	ft/sec	grams	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
				Type C-b screen with 0.040-inch slots (cont'd.)											
1/4	20-30	0.0186	2.1	14.8	9.39	4.51	1.88	1.33	.27	.08	--	.06	.00	- .04	- .12
		.0373	6.4	30.6	19.85	10.06	4.45	2.91	1.31	.65	--	.22	.15	.04	- .13
		.0751	17.2	--	33.83	16.66	8.71	5.96	3.50	2.19	1.06	.93	.73	.40	- .01
		.125	25.4	93.9	55.39	26.29	12.18	8.70	4.61	2.19	--	1.79	1.40	.77	- .01
		.149	49.9	128.2	79.2	46.8	24.1	16.5	10.5	6.7	4.3	3.5	2.55	1.46	.15
1/4	30-40	.0119	27.9	17.32	9.69	4.09	1.35	.27	.38	.16	---	.03	.02	- .01	- .03
		.0183	33.2	26.96	14.84	5.91	1.80	.96	.38	--	--	.11	.09	.04	- .01
		.0383	80.8	59.8	32.12	13.53	4.45	2.27	1.27	.87	--	.18	.15	.06	- .09
		.0606	124.7	91.7	49.35	21.95	8.98	5.84	3.69	1.28	--	.76	.57	.34	.04
		.0639	170.6	103.5	55.03	21.0	8.47	6.13	4.06	2.63	--	1.23	.42	.21	- .07
				Typo C-c screen with 0.100-inch slots											
1/16	20-30	.0376	0.0	19.49	12.02	6.71	4.00	3.19	2.54	--	2.40	--	1.86	1.03	0.20
		.0745	3.0	40.83	25.01	13.85	8.36	6.58	5.16	--	4.29	--	3.70	2.06	.39
		.149	1.8	83.8	53.86	--	19.26	16.15	12.87	10.70	--	--	6.56	4.17	.87
1/16	30-40	.0192	1.5	28.9	16.42	8.65	4.54	3.25	1.85	1.27	--	1.15	.93	.50	.04
		.0382	1.1	59.5	33.66	16.89	8.47	6.09	3.20	2.95	--	2.75	2.18	1.21	.11
		.0627	1.1	103.0	56.15	27.06	13.20	9.29	5.29	5.10	--	--	3.85	2.11	.22
1/16	40-60	.0123	.8	41.64	22.30	11.09	5.72	4.90	2.86	1.91	--	.89	.71	.39	.05
		.0199	1.9	68.5	35.66	16.71	6.92	4.05	1.45	--	--	--	.96	.52	.03
		.0302	1.1	103.81	58.71	29.77	14.57	10.14	5.09	2.36	--	2.15	1.69	.98	.21
1/8	30-40	.0192	1.5	32.5	18.76	9.14	4.32	2.81	1.53	.49	--	.43	.31	.12	- .07
		.0382	2.1	63.2	37.56	19.60	10.58	8.00	5.39	3.08	--	.89	.71	.35	- .09
		.058	4.1	102.5	57.93	26.03	11.59	7.81	3.23	1.94	--	1.72	1.34	.73	- .05
1/8	40-60	.0099	3.4	36.9	20.50	19.55	4.23	2.69	1.25	.46	--	.23	.16	.05	- .02
		.0198	5.5	74.4	40.42	18.87	8.96	6.28	4.04	1.07	--	.43	.33	.16	- .05
		.0299	10.7	104.2	57.51	26.62	12.06	8.10	3.73	1.47	--	.53	.41	.16	- .19
		.0797	68.7	--	--	--	--	--	--	--	--	--	--	--	--

Table 6.-- Loss of head through sand and gravel in model study of flow of sand into wells for various combinations of screen, sand and gravel. (Continued)
(Loss of head measured between piezometer indicated and piezometer No. 1 (see figure).

Size Gravel	Size Sand	Velocity in sand	Sand Moved	Piezometer Number 2	3	4	5	6	7	8	9	10	13	14	15
in.	Screen No.	ft/sec	grams	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
				Type C-c screen with 0.100-inch slots (cont'd.)											
1/4	10-14	.0378	0.4	4.21	2.62	1.35	.68	.52	.31	.26	--	.23	.16	.06	- .05
		.0754	.4	10.18	6.45	3.50	1.99	1.57	1.10	.81	--	.73	.59	.32	- .05
		.151	1.0	23.90	15.50	8.93	5.48	4.47	3.65	2.76	--	2.26	1.61	1.02	.05
1/4	20-30	.0107	2.3	5.78	3.64	1.70	.66	.37	.16	.15	--	.14	.14	.13	.07
		.0185	8.0	9.90	6.07	2.39	1.28	.80	.39	.21	--	.17	.16	.10	.05
		.0187	3.5	11.18	6.99	4.59	1.75	1.18	.64	.34	--	.29	.30	.25	.10
		.0373	5.5	19.02	11.95	5.97	2.72	1.72	1.02	.47	--	.43	.40	.29	.16
		.0705	7.6	36.15	21.86	10.05	3.52	1.81	1.09	--	--	.77	.66	.37	.00
		.149	59.8	123.5	74.5	42.9	24.6	18.6	1.24	.56	3.61	3.06	2.63	1.57	.44
		.151	23.5	73.6	43.09	18.52	6.15	3.09	2.67	--	--	2.34	1.96	1.16	.16
1/4	30-40	.0191	32.3	32.6	18.90	9.49	4.60	3.26	1.85	.98	.17	.15	.12	.06	- .02
		.0192	26.1	29.2	16.58	7.67	3.27	2.22	1.02	.25	- .19	- .18	- .22	- .25	- .34
		.0382	70.0	55.0	30.81	13.46	5.29	3.45	1.95	.96	.34	--	.24	.14	- .04
		.0606	142.8	87.0	47.17	20.64	8.20	5.64	3.82	2.21	--	.80	.49	.20	- .06
		.0716	293.0	100.2	58.15	27.05	13.53	9.93	6.99	5.42	--	1.68	.80	.37	.03
1/2	14.20	.0370	1.5	9.75	5.81	2.66	1.10	.54	.12	.02	--	.00	- .03	- .06	- .10
		.0738	1.7	20.90	--	--	--	--	--	--	--	--	--	--	--
		.150	6.9	42.5	--	7.15	5.11	3.27	2.21	1.83	--	1.76	.65	.28	- .05
				Type C-d screen with 0.200-inch slots											
1/4	14-20	.037	1.5	8.56	5.01	2.40	0.85	0.53	0.32	--	--	0.22	0.23	0.12	- .05
		.0739	2.7	21.05	13.57	6.56	3.21	2.31	1.36	0.80	--	.79	.61	.36	.05
		.152	4.2	44.42	28.18	14.85	8.23	6.40	4.35	2.80	--	2.65	1.93	1.15	.15
1/4	20-30	.0186	1.8	15.8	10.16	5.06	2.26	1.49	.38	.05	- .14	- .13	- .15	- .22	- .26
		.0370	3.5	28.4	17.92	9.22	4.45	3.08	1.77	.57	--	.27	.22	.07	- .04
		.0744	10.4	56.6	34.68	16.79	7.37	4.53	1.59	.88	--	.84	.63	.43	- .04
		.123	25.4	90.7	53.04	23.85	8.35	5.37	3.54	2.41	--	1.98	1.54	.85	.13
		.149	55.8	121.0	72.0	41.9	23.8	16.8	11.7	6.70	3.46	3.25	2.17	1.25	.17

Table 6.-- Loss of head through sand and gravel in model study of flow of sand into wells for various combinations of screen, sand and gravel. (Continued)
(Loss of head measured between piezometer indicated and piezometer No. 1 (see figure).

Size Gravel	Size Sand	Velocity in sand	Sand Moved	Piezometer Number 2	3	4	5	6	7	8	9	10	13	14	15
in.	Screen No.	ft/sec	grams	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Type C-d screen with 0.200-inch slots (cont'd)															
1/4	30-40	0.0119	24.8	19.3	10.98	5.02	2.12	1.38	0.66	0.18	0.08	0.08	- .01	- .03	- .07
		.0192	41.1	30.1	16.51	7.21	2.66	1.61	.61	.27	--	.18	.13	.02	- .01
		.0382	82.8	59.8	33.79	15.19	5.68	2.69	1.26	.39	--	- .11	- .17	- .34	- .46
		.0606	152.6	102.1	55.41	24.61	10.56	7.29	4.21	2.56	--	.83	.54	.31	.05
1/2	10-14	.0374	.5	5.06	2.46	1.09	.51	.33	.15	.06	--	.03	.01	.00	- .03
		.0750	.5	9.11	5.44	2.67	1.24	.85	.38	.28	--	.26	.21	.09	- .02
		.151	1.4	20.88	12.67	6.46	3.22	2.40	1.44	.78	--	.73	.61	.23	- .12
1/2	14-20	.0369	1.4	11.1	6.80	3.47	1.82	1.34	.81	.43	.06	.07	.06	- .04	- .06
		.0741	1.6	23.2	14.16	7.32	3.65	2.76	1.75	.75	.15	.15	.07	- .03	- .14
		.148	6.1	48.93	28.19	12.96	5.00	2.90	1.00	.99	--	.89	.69	.39	.01
		.149	13.5	48.6	29.86	15.42	8.04	6.02	3.94	1.72	--	.84	.64	.35	- .01
Type B-a screen with 1/16-inch perforations															
1/16	40-60	.0123	1.0=	50.0	29.53	15.72	8.96	7.06	4.97	3.13	1.26	1.22	.96	.48	.04
		.0199	1.0	74.3	--	21.25	9.94	6.87	3.44	2.23	--	2.06	1.68	.95	.21
		.0289	1.3	103.6	60.56	27.88	11.76	7.14	2.95	2.84	--	2.65	2.08	1.06	.04
		.0797	2.8	289.7	173.8	91.3	49.1	--	26.3	15.7	13.8	13.4	11.35	7.01	2.59
1/8	30-40	.019	4.0	30.90	17.64	7.83	3.02	1.63	.53	.52	--	.48	.38	.23	.02
		.0382	5.6	--	39.96	20.69	10.89	8.50	6.00	3.60	1.29	--	.80	.58	.17
		.0579	4.5	92.7	52.18	26.15	13.18	9.69	5.52	3.22	1.97	1.89	1.58	.98	.30
		.0583	7.0	--	59.36	27.52	11.61	6.91	3.46	2.14	--	1.96	1.64	1.06	.42
		.152	16.5	278.0	--	91.0	55.9	--	33.8	24.6	15.3	11.1	9.0	6.2	3.2
Type B-b screen with 1/8-inch perforations															
1/8	30-40	.019	1.4	33.5	20.22	9.74	4.46	2.94	1.16	.06	--	- .02	- .12	- .31	- .49
		.0382	3.1	66.8	39.40	18.84	8.71	5.97	2.74	1.15	--	1.05	.84	.46	.04
		.0551	3.6	103.1	62.42	31.74	15.42	10.51	3.06	1.55	--	1.41	1.07	.42	- .30
1/4	20-30	.0186	2.7	14.40	8.23	3.77	1.39	.72	.01	- .01	--	- .02	- .06	- .09	- .18
		.0376	5.3	28.90	17.37	8.46	3.78	2.48	1.02	.42	--	.32	.26	.12	- .04
		.0755	16.7	61.6	--	18.71	9.03	6.33	3.66	2.32	1.33	--	.91	.56	.16
		.122	25.0	94.9	55.70	25.59	9.70	5.69	2.98	2.28	--	2.18	1.76	1.08	.29
		.149	55.4	119.1	71.0	30.7	19.8	13.0	8.4	4.37	3.24	3.18	2.58	1.57	.36

Table 6.-- Loss of head through sand and gravel in model study of flow of sand into wells for various combinations of screen, sand and gravel. (Continued)

(Loss of head measured between piezometer indicated and piezometer No. 1 (see figure).

Size		Velocity	Sand	Piezometer Number											
Gravel	Sand	in sand	Moved	2	3	4	5	6	7	8	9	10	13	14	15
in.	Screen No.	ft/sec	grams	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Type B-c screen with 3/16-inch perforations															
1/4	20-30	0.0185	2.4	17.30	10.45	5.01	2.01	1.25	0.36	0.15	--	0.14	0.10	0.05	- .04
		.0373	4.0	31.9	20.00	9.69	4.11	2.51	.57	.47	--	.30	.21	.10	- .06
		.0744	14.2	61.7	38.18	19.59	9.97	7.15	3.24	1.46	--	1.03	.83	.53	.05
		.119	30.0	95.8	57.91	28.69	13.10	8.46	4.66	3.16	--	2.00	1.57	.88	.12
		.149	55.0	118.4	66.2	41.4	22.2	15.4	10.1	6.2	3.45	3.32	2.55	1.61	.51
1/2	14-20	.0378	1.8	14.30	8.85	4.54	2.16	1.62	1.00	.45	--	.04	.03	- .01	- .07
		.0733	3.4	29.31	18.65	9.46	4.57	3.10	1.37	.62	.24	.25	.17	.08	- .04
		.148	6.3	50.3	30.15	14.63	6.77	4.46	2.41	1.12	--	1.05	.83	.58	.18
		.148	16.5	57.0	36.72	19.52	10.88	8.27	5.44	3.17	.46	.42	.26	.00	- .39
Type D-a screen with 1/16-inch perforations															
1/16	40-60	.0199	1.9	75.3	--	22.36	12.16	9.29	6.26	2.94	--	2.27	1.87	1.12	.27
		.0792	2.5	300.5	173.5	91.5	53.6	--	33.6	24.0	12.96	12.45	10.44	6.33	1.93
1/8	30-40	.0383	4.5	70.3	42.37	23.57	13.58	10.29	6.61	3.08	1.48	1.47	1.25	.82	.32
		.0764	6.2	116.9	61.5	33.5	17.7	13.50	9.08	5.41	3.65	3.56	2.97	1.97	.86
		.152	14.5	264.7	158.7	72.3	51.1	41.8	32.6	23.1	13.9	11.5	--	6.73	3.81
Type D-b screen with 1/8-inch perforations															
1/8	30-40	.0380	4.1	53.9	28.67	13.78	6.91	5.22	3.22	1.55	1.06	1.03	.32	.46	.06
		.0764	8.4	126.2	74.0	41.1	22.41	16.81	11.26	6.68	3.32	3.02	2.43	1.41	.40
		.152	15.7	259.7	150.2	7.52	--	32.4	21.1	12.8	9.30	8.84	7.06	4.51	1.69
1/4	20-30	.0373	4.6	31.53	19.27	10.30	5.11	3.69	2.11	.73	.26	.27	.20	.03	- .10
		.0744	22.3	46.8	26.7	12.86	6.20	4.43	2.68	1.56	1.17	1.07	.89	.56	.16
		.150	66.6	116.7	73.1	38.7	17.7	10.9	6.6	4.6	--	4.0	3.26	2.35	1.03
Type D-c screen with 3/16-inch perforations															
1/4	20-30	.0373	4.5	30.46	19.05	9.59	4.35	2.69	1.26	.41	--	.36	.28	.16	- .02
		.0744	14.3	48.8	28.75	14.60	7.47	5.32	3.26	1.23	1.14	1.14	.95	.62	.27
		.150	65.9	117.1	69.6	38.7	29.4	14.4	10.62	7.22	4.06	3.73	3.03	2.10	.83
1/2	14-20	.0378	1.6	10.71	6.35	3.01	1.30	.86	.46	.09	.04	.04	.02	- .02	- .06
		.0738	5.5	22.27	13.25	6.64	3.44	2.61	1.80	1.16	.36	.34	.30	.21	.06
		.149	10.7	49.1	29.66	14.64	6.86	4.90	2.56	1.29	--	1.26	1.06	.66	.25

head losses measured in the gravel envelope where the losses are small. Since some of the losses are negative, the manometer readings at these piezometers were less than the reading for the piezometer (No. 1) in the chamber at the end of the plastic tube. It was thought that this might be due to the fact that the velocity in the gravel was higher than that in the chamber. Since the velocity was higher, the pressure would have to be lower. However, computation of the change in velocity head for the change in velocity at the very low velocities involved, showed that the differences in head due to this factor were too small to account for the negative readings.

These negative readings cannot be dismissed as errors in reading because there is a progressive change in the head losses through the gravel from the interface to the well screen even when the negative readings occur. The most plausible explanation for the negative losses is that the head indicated by Piezometer No. 1 was too high at the instant the clamp was applied to the tubes. This could happen because this piezometer would be more active than the ones in the sand and gravel where sand particles would tend to clog the screen in the piezometer openings.

Most of the negative losses are less than 0.1 inch, but in a few tests they are higher. The magnitude of the negative losses is probably some indication of the accuracy of the head measurements of the piezometers. However, it cannot be assumed that the negative readings are caused entirely by the failure of the piezometers to indicate the head correctly. These readings are probably the result of the cumulative effect of various factors.

The interface between the sand and gravel was normally at Piezometer No. 8, but some deviation from this location occurred because it was not possible to tell exactly where the interface would come after the sand and gravel column had been compacted. As is shown by the tables nearly all the loss occurred between the upper end of the column, Piezometer No. 2 and Piezometer No. 8, at the interface. The reason that the difference in losses at Piezometer No. 5, 6, 7 and 8 is small is that the distance between these piezometers is only a fraction of an inch. For Piezometers No. 9, 10, 13, 14 and 15 the losses are small, because these piezometers measure the loss through the gravel. The data indicate that the loss through the gravel increased when a large quantity of sand was washed into it but since the velocity was also higher when this occurred it is not evident how much of the increase was due to each cause.

For the tests on each combination of screen, sand and gravel, the total loss through the sand and gravel increases with the velocity. According to Darcy's law the losses should increase in direct proportion to the increase in velocity. Since the tests were arranged so that each succeeding velocity was double the preceeding one, the total head losses should also double. Although this is approximately true for some of the tests there are many exceptions. The deviations are probably caused by the changes that occurred in the sand and gravel. Since the velocity of the water causes a rearrangement of the sand particles and since the magnitude of the changes increases with the velocity, the head losses may vary consideratly. Furthermore, the amount of sand moved also affects the losses and their distribution in the sand and gravel column. For this reason much greater variation is to be expected in the losses in short lengths of the sand and gravel column. This is clearly shown by the indicated losses in the table from Piezometer No. 5 to No. 15. In general, the losses increase with the velocity, but there are some exceptions.

Where check tests were made, in cases where piping was observed or where excessive air accumulation occurred in the plastic tube, wide differences in the losses were found. This is due to the fact that there is practically no resistance to the flow when piping occurs, whereas the resistance is increased when air is trapped in the sand and gravel.

As should be expected, the size of the sand particles was the most significant factor in determining the head loss. The size of the gravel also had some effect but since the loss through the gravel is small it was overshadowed by the loss through the sand. The well screen probably had some effect, although this is not clearly evident from the tests. However, since it has been shown in previous Progress Reports* that there are limiting values for the percentage of openings in screens, beyond which the loss remains constant, no definite trend in the losses should be expected from these tests.

These head loss studies were incidental to the main purpose of the tests, which was to investigate the flow of sand into wells. For this reason the losses were based on single readings of the manometers. Because of the fact that the head in the manometers flucturates and further, because there is a gradual change in the head due to the rearrangement of the particles in the sand and gravel during the test, a single reading of the manometer is not always indicative of the true head at the point where the piezometer is located. Much better results would be obtained if the losses were based on the average of several readings.

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* Hydraulic Properties of Well Screens, by Gilbert Lee Corey, Jr., Graduate Thesis, Colorado A and M College, 1949.

Effect of Well Screens on Flow into Wells, by Jack S. Petersen, Carl Rohwer, and M. L. Albertson. Unpublished paper, 1952.

DEVELOPMENT OF NATURAL GRAVEL ENVELOPE BY SURGING

Whenever the water bearing formation is made up of well graded material of a wide range of sizes it should be possible to form a natural gravel envelope around the well screen by developing the formation. After the well has been developed by surging, pumping or other means, only the coarsest material should remain around the well screen and as the distance from the screen increases, the coarseness of the material should decrease, thus forming a natural gravel envelope. The effectiveness of this type of gravel envelope is determined by how satisfactory it is in controlling the flow of sand and in reducing the loss of head. In the experiments reported here only the effect on the loss of head was studied. The amount of sand washed out of the formation was measured because it was thought that it would be a measure of the effectiveness of the development of the formation.

Method of Conducting Tests to Form Natural Gravel Envelopes

The original plan for conducting the tests to form a natural gravel envelope by surging was to put the water bearing material and well screen in the model previously used and then to develop the formation by surging with a surge block. This plan had to be abandoned because it was not possible to move the surge block fast enough to do an effective job of developing the formation and furthermore as the fine material was removed from the sand the formation settled away from the top of the tube. When this occurred, the head losses were no longer significant because the water flowed over the sand rather than through it.

While these preliminary tests were in progress it was discovered that surging by alternately starting and stopping the flow through the model was much more effective than the surge block. A quick-opening spring valve in the outlet from the model was found to produce the quick surges in the flow necessary to develop the formation.

In view of the fact that the effectiveness of the surging could not be measured when the model was in the horizontal position owing to the settlement of the formation in the model, it was decided that the study would have to be conducted with the model in the vertical position. With the model in this position there would be no tendency for the sand to settle away from the walls of the model. The whole column would move downward as the fine sand was removed by surging. No doubt the fine particles would wash out of the formation more freely when moving vertically downward with the help of gravity than when moving horizontally under the influence of the surging action alone. However, the surging action is so much more vigorous than the action of gravity, especially since the weight of the sand particles is reduced by the buoyant effect of the water, that the effect of gravity is relatively small. Furthermore, the purpose of this study was to determine whether a satisfactory natural gravel envelope could be formed around the screen by developing the well. The fact that the natural gravel envelope might be formed more quickly in the vertical position is not a factor in the problem.

A plastic tube 25 inches in length was used for these tests. (See figure 16.) A general view of the equipment is shown in figure 17. The other parts of the equipment were the same as before except for the quick-opening spring valve which was screwed into the bottom plate. Water for the experiments was drawn from a tank about 20 feet above the model. An attempt was made to use water from the city supply at full pressure but this did not prove feasible because the water hammer blew the tubes off the piezometer connections.

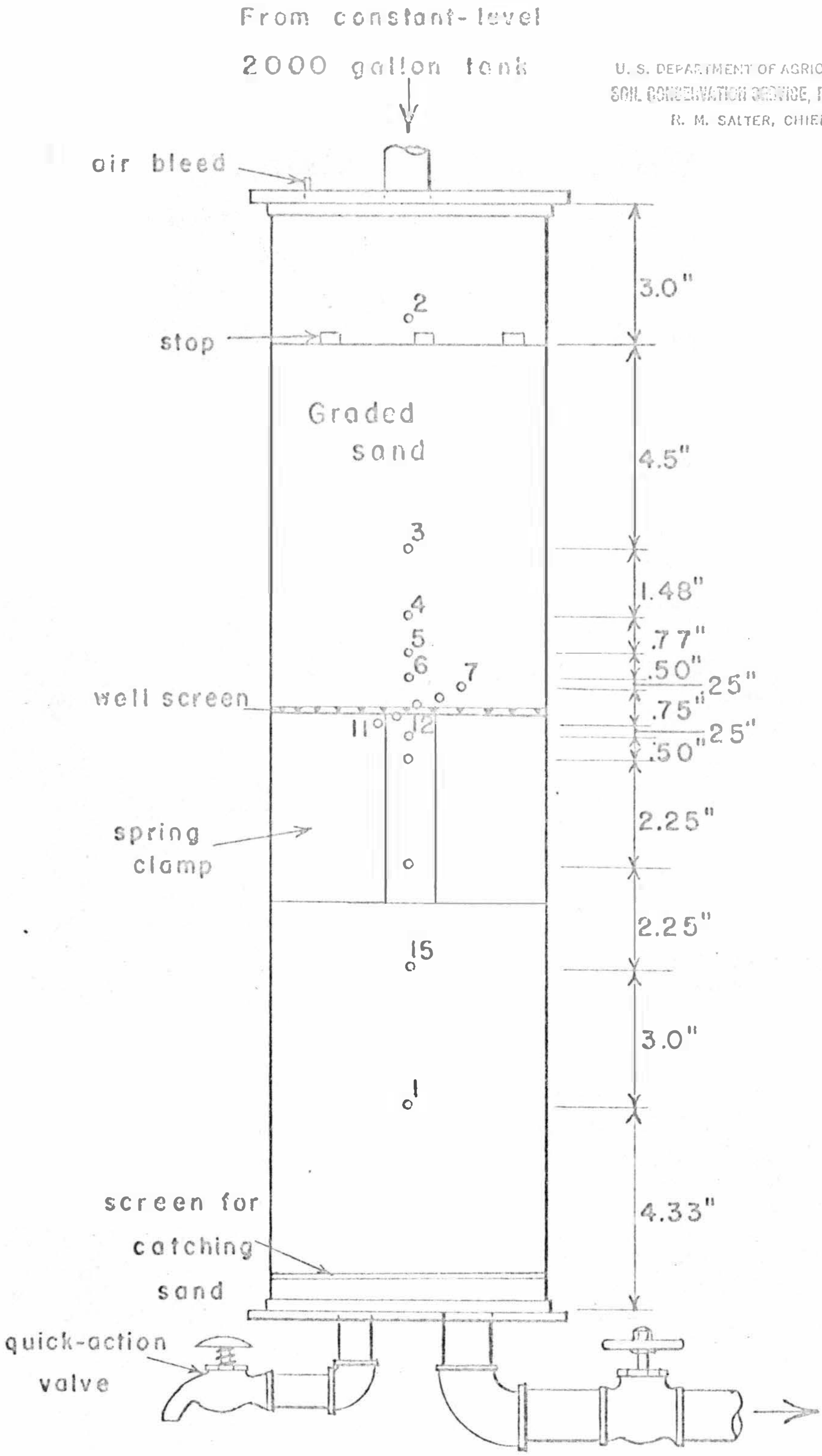

Figure 16 .- Equipment for studying effect of surging.

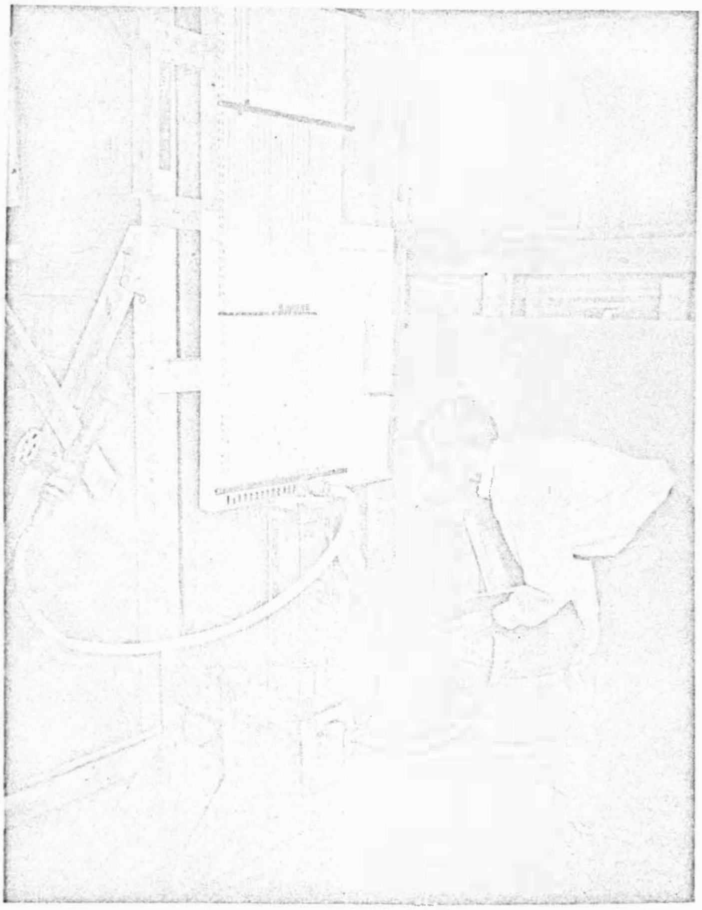

Figure 17.-- Arrangement of equipment for model study of formation of natural gravel envelope by surging.

Screens of four different types were used in the tests but only one sand. This sand had the characteristics shown in figure 4. (See curve marked graded sand.) It was formed by adding several sizes of gravel to a graded sand.

The loss of head through the formation was determined before and after surging for two different discharges for each screen tested. The heads at the piezometer connections were read on the manometer board in the same manner as before and the technique in placing the sand and in measuring the discharge was the same as that used previously.

In making a test the valves in the inlet and outlet pipes were adjusted until the desired quantity was flowing through the model as indicated by the head on the orifice in the discharge tank. When the flow had been adjusted and 30 minutes after the water had been turned on, the heads at the various piezometer connections were read. The water was then shut off at the outlet valve and surging started. Surging consisted of opening and closing the quick-acting spring valve 100 times for each test. Since it was desirable to determine whether further surging would continue to improve the gravel envelope, the treatment was repeated several times at the lower discharge rate. At the end of each series of surges the outlet valve was again opened and the flow adjusted to the desired quantity. As soon as the flow was adjusted the heads were read. After 15 to 20 minutes the initial readings for the next series were taken. At the end of the series of tests the sand washed out of the formation was collected, dried and weighed. The records of the tests were kept on the forms used for the study of the flow of sand into wells.

Results of Tests on Natural Gravel Envelopes

According to Bennison*, any water-bearing formation having an effective size greater than 0.01 inch and a uniformity coefficient greater than 2, does not require a gravelenvelope to develop the full capacity of the formation. If a screen with the proper size of opening is used such a formation will produce a natural gravel envelope if the well is developed properly.

The material used for the water bearing formation in the model study of the development of a natural gravel envelope had an effective size of 0.02 inch and a uniformity coefficient of 2.4, which is within the limits recommended by Bennison. A larger size of screen opening than would normally be adopted for an irrigation well in this formation was used in the model study because the preliminary tests showed that large openings were necessary. Because the surging action in the model was not as violent as that which would be produced in a full-size well, large openings had to be used in order to wash sufficient fine material out of the formation to produce the desired results. The tests indicate however, that the surging action was not as strong as should have been used.

The results of this study are set forth in table 7. The head losses which were measured between the points indicated by the piezometer numbers on the left side of the table and the chamber in the tube at the bottom of the sand column (see figure 16) are shown in the table in the column opposite the indicated piezometer. The losses before and after surging are shown in adjoining columns. All the losses are in inches of water.

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* Ground Water, its Development, Uses and Conservation by E. W. Bennison, Edward E. Johnson, Inc., Saint Paul, Minnesota, 1947 (see page 257).

Table 7.-- Summary of results of tests for developing a natural gravel envelope in a well by surging, showing head losses before and after surging and amount of sand washed out of formation.

Piez. No.	Dist-* ance	Discharge 2.57 gpm							Discharge 5.14 gpm		
		First Surge Loss of Head#		Second Surge Loss of Head#		Third Surge Loss of Head#		Sand Washed Out	First Surge Loss of Head#		Sand Washed Out
		Before	After	Before	After	Before	After		Before	After	
	Inch	Inch	Inch	Inch	Inch	Inch	Inch	Grams	Inch	Inch	Grams
		Type B screen with 1/8-inch perforations									
2	0	53.57	45.15	45.48	44.09	44.64	43.82	124.4	152.5*	134.1*	56.3
3	4.5	25.25	19.12	19.07	18.45	18.34	18.13		87.2*	73.6*	
4	5.98	13.18	9.75	9.75	9.40	9.26	9.28		43.65	30.61	
5	6.75	7.46	5.71	5.68	5.58	5.53	5.44		29.57	18.61	
6	7.25	4.62	2.91	2.96	2.90	2.85	2.97		20.36	11.98	
7	7.50	3.35	2.43	2.53	2.55	2.52	2.68		13.45	6.76	
8	7.68	.76	1.28	1.33	1.67	1.65	1.73		5.87	5.97	
9	7.87	.10	.03	.99	.25	.22	.25		3.86	4.20	
10	8.06	.07	.01	.06	.11	.05	.00		--	--	
11	8.25	- .05	- .15	- .12	- .03	- .06	- .07		3.10	3.08	
12	8.50	--	--	--	--	--	--		- .15	- .02	
		Type C screen with 0.100-inch slot									
2	0	48.44	44.00	44.38	43.31	44.36	42.85	275.6	126.4*	121.3*	249.3
3	4.5	20.95	19.28	19.06	18.35	18.52	18.00		--	--	
4	5.98	9.97	9.51	9.28	8.72	8.74	8.26		25.31	22.74	
5	6.75	4.07	4.50	4.34	3.59	3.60	3.50		12.94	10.89	
6	7.25	1.55	1.68	1.65	1.48	1.43	1.43		5.37	3.61	
7	7.50	.63	.65	.56	.65	.61	.57		2.01	1.26	
8	7.68	.24	.39	.35	.43	.42	.34		--	.40	
9	7.87	.00	.07	.01	.01	- .04	- .03		.30	.09	
10	8.06	- .03	- .03	- .06	- .04	- .09	- .10		.03	- .04	
11	8.25	--	--	--	--	--	--		- .09	- .04	
12	8.50	- .05	- .04	- .08	- .05	- .09	- .10		--	- .04	

* Piezometer readings made with mercury manometer.
\# Loss through sand measured between piezometer and water at bottom of sand column.

Table 7.-- Summary of results of tests for developing a natural gravel (Continued) envelope in a well by surging, showing head losses before and after surging and amount of sand washed out of formation.

Piez. No.	Dist-* ance	Discharge 2.57 gpm							Discharge 5.14 gpm		
		First Surge Loss of Head#		Second Surge Loss of Head#		Third Surge Loss of Head#		Sand Washed Out	First Surge Loss of Head#		Sand Washed Out
		Before	After	Before	After	Before	After		Before	After	
	Inch	Inch	Inch	Inch	Inch	Inch	Inch	Grams	Inch	Inch	Grams
					Type D screen with 1/8-inch perforations						
2	0	50.09	41.87	42.62	42.28	43.03	42.63	139.9	131.0*	117.4*	128.5
3	4.5	22.76	17.01	17.07	16.95	17.23	17.15		74.0*	67.8*	
4	5.98	13.28	8.51	8.56	8.61	8.78	8.76		33.78	25.40	
5	6.75	8.23	4.73	4.85	4.88	5.05	5.04		19.55	14.44	
6	7.25	5.29	2.93	3.05	3.14	3.30	3.37		11.74	8.63	
7	7.50	2.85	1.62	1.66	1.89	2.09	2.26		9.04	6.91	
8	7.68	1.95	1.53	1.61	1.84	2.00	2.06		4.35	4.14	
9	7.87	1.68	1.32	1.42	1.46	1.62	1.66		3.64	2.91	
10	8.06	1.16	.74	.77	.73	.86	.90		.24	.07	
11	8.25	--	--	--	--	--	--		.24	.02	
12	8.50	- .07	-1.0	- .03	- .11	.00	- .05		--	--	
					Type F screen with 0.145-inch openings						
2	0	45.61	42.47	42.79	41.58	42.38	41.23	183.5	123.2*	117.6*	201.4
3	4.5	18.85	17.69	17.35	16.94	17.07	16.61		66.1*	62.2*	
4	5.98	9.39	8.85	8.64	8.02	8.13	7.90		25.05	21.45	
5	6.75	4.49	4.04	3.39	3.66	3.64	3.74		13.63	11.01	
6	7.25	1.48	1.77	1.64	1.56	1.54	1.70		7.04	5.61	
7	7.50	.77	.91	.90	.98	.94	.91		3.85	2.71	
8	7.68	.07	.61	.46	.39	.50	.40		2.15	1.98	
9	7.87	.02	.03	- .06	- .01	.04	.00		.58	.82	
10	8.06	- .02	.02	- .06	- .02	- .06	- .05		--	--	
11	8.25	--	--	--	--	--	--		.75	.02	
12	8.50	- .03	+ .02	- .06	--	- .05	- .05		- .04	--	

* Piezometer readings made with mercury manometer.

\# Loss through sand measured between piezometer and water at bottom of sand column.

As was noted in the tests on the flow of sand into wells, negative losses were observed for the piezometers near the bottom of the sand column just above the well screen. Since nearly all the losses in this area are negative they must be caused eitherby a systematic error in the readings or by some cause that has not been identified. Fortunately the negative readings are all small and therefore probably do not affect the conclusions which may be drawn from these tests.

Since the same sand was used for all the tests and the same technique was used in compacting the material in the model, it was thought that the total loss through the sand column before surging should be constant. However, the losses differ considerably as shown by the table. This difference is probably due in part to the fact that the measured loss includes the loss through the screen. Experiments by Corey* indicate that there is a significant difference between the losses through the different screens if the percentage of openings in any of the screens is less than 15. Since the type B and the type D screens fall in that category, reasonably constant losses would probably be obtained if it were possible to eliminate the effect of the losses through the screens.

In every test, surging was effective in reducing the head loss through the sand and the well screen. This is shown graphically in figure 18, which is a plot of the losses before and after surging for the tests at the lower velocity. The greatest reduction occurred in the screens with the smallest percentage of openings. An interesting fact to be noted in these tests is that after surging all the losses tended to approach the same value except

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* Hydraulic Properties of Well Screens, by Gilbert Lee Corey, Jr., Graduate Thesis, Colorado A and M College, 1949.

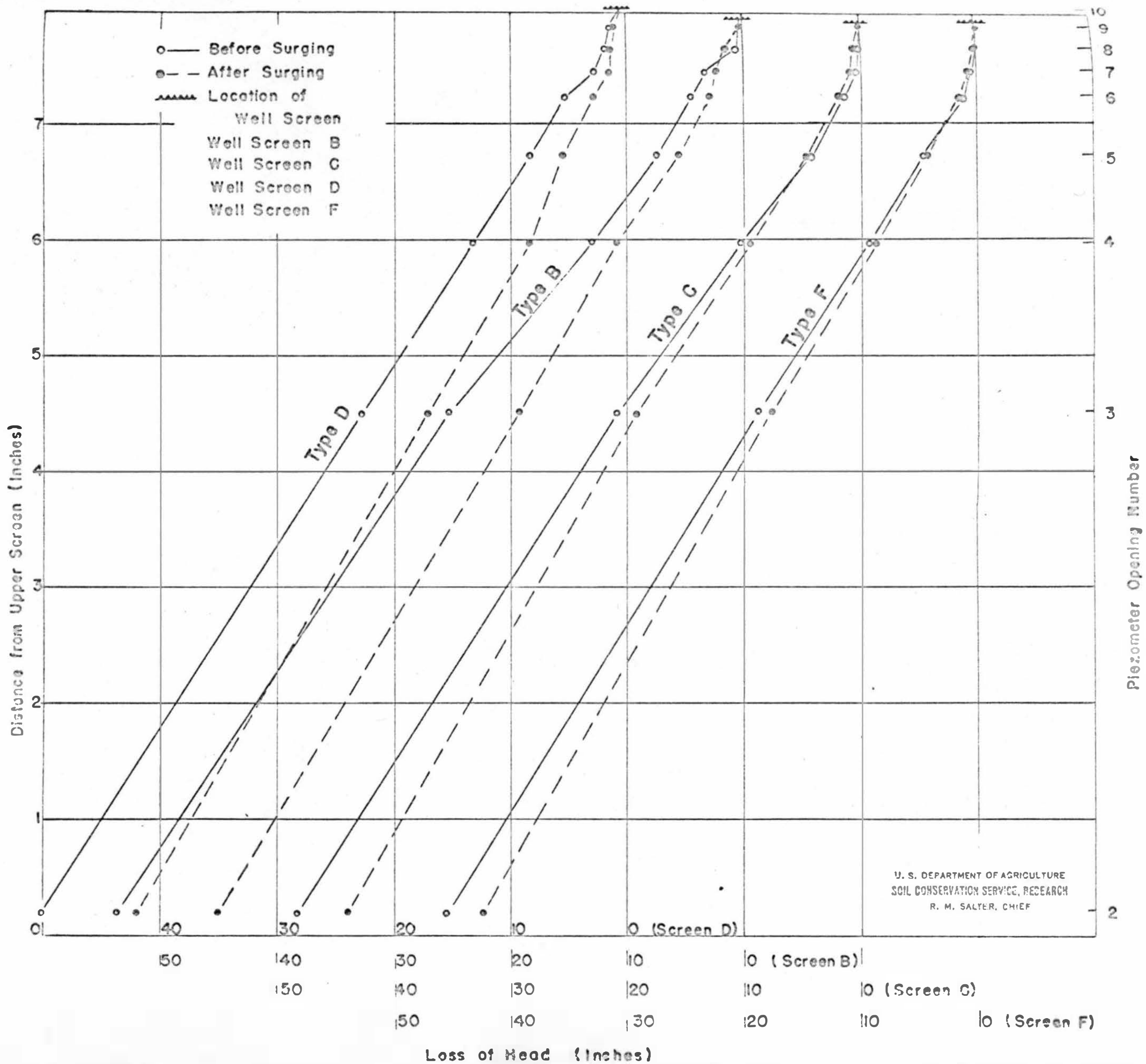

Figure 18 - Loss of head through sand before and after surging. Minimum discharge.

in the test on the type B screen at maximum discharge. (See table 7.) Since the amount of sand washed out during this test seems to be too small in comparison with the others, it may be assumed that the conditions were not the same as in the othertests. These tests show that the surging action was more effective for the screens with the smaller percentage of openings. A suggested explanation of this phenomenon is that the higher velocities through the perforations in the screens with the smaller percentage of openings, made the surging more effective. However, more sand was washed out through the screens with more open area but this was to be expected because there was more open area for the sand to come through. As a result the washing action was distributed over a large area and consequently it did not take out enough of the fine material to produce the maximum effect in reducing the loss of head. These results support the belief that a more violent surging action should have been developed during the tests.

This belief is given further support by the fact that additional surging during the tests at the lower discharge had little effect in reducing the head loss. Had the effect of additional surging during the tests at the higher discharge been investigated, further reduction in the head loss would probably have resulted. These tests were not considered necessary at the time because the tests at the lower discharge showed that all the improvement occurred during the first period of surging.

Although it was possible to see the sand move during surging, a definite gradation could not be observed in the sand near the well screen after the surging was completed. Apparently a much longer period of surging would be required before the gradation of the sand would become visible to the eye.

These tests were probably too limited in scope to warrant drawing definite conclusions as to the possibility of forming a natural gravel envelope by this method but they do show that development of the formation by surging reduces the loss of head.

RECOMMENDATIONS FOR FUTURE WORK

Although a large number of tests was made on the flow of sand into wells, the analysis of the results shows that additional tests will have to be made before definite conclusions can be drawn. The various combinations of sand for the water bearing formation, gravel for the gravel envelope and size of openings for the screen, were most completely covered for the screens with continuous slots. Additional tests will have to be made on the lattice and the punched screens with different sizes of sand and gravel. A sufficient range of sizes of perforations was tested for these screens but the combinations of sand and gravel were too limited. Furthermore, the tests on all the screens should cover a more complete range of velocities for the different sand and gravel combinations. The effect of using graded sands and gravels should also be studied.

In the study of the loss of head for the tests on the flow of sand into wells and on the development of a natural gravel envelope, the cause of the negative losses in the region near the well screen should be investigated.

The study of the formation of a natural gravel envelope by surging should be continued. Means for producing a more powerful surging action in the model should be devised. A wider range of conditions will have to be investigated before it will be possible to make definite recommendations as to the condition for which it is feasible to use this method for producing a gravel envelope.

Since the procedure in preparing for the tests and in conducting them in problems of this type is very important, attention should be given to developing a technique that will yield more consistent results.

SUMMARY

The results of the model study of the flow of sand into wells when using sand and gravel with particles of uniform size, indicate that the ratio of the size of sand in the water-bearing formation to the size of gravel in the gravel envelope, determines how much material will be washed out of the formation at a definite velocity if the velocity is sufficient to move the sand particles. However, more data will have to be obtained before it will be possible to fix the limits of the ratios for different velocities.

If the openings in the screen are large enough to pass the sand particles, and hold back the gravel of the gravel envelope, the size of the openings has little if any effect on the amount of sand moved. For the range of conditions tested the type of screen also had little effect on the amount of sand moved except at high velocities.

The limited tests on the development of a natural gravel envelope by surging show that the development process reduces the head loss through the formation and the reduction in head loss is greatest for screens with a small percentage of openings. This characteristic is attributed to the fact that for the conditions of the tests, the velocity caused by the surging was concentrated in a smaller area when the percentage of openings was small, and consequently the surging action was more violent than for the screens with a large percentage of openings.

All the statements made in the summary are tentative because they are based on a limited number of tests. It may be necessary to change some of them when more data become available.