J. M. Kernodle

Specific Yield— Laboratory Experiments Showing the Effect of Time on Column Drainage

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1662-B

Prepared in cooperation with the California Department of Water Resources

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By R. C. PRILL, A. I. JOHNSON, *and* D. A. MORRIS

HYDROLOGIC PROPERTIES OF EARTH MATERIALS

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SPECIFIC YIELD—LABORATORY EXPERIMENTS SHOWING THE EFFECT OF TIME ON COLUMN DRAINAGE

By R. C. Prill, A. I. Johnson, and D. A. Morris

ABSTRACT

The increasing use of ground water from many major aquifers in the United States has required a more thorough understanding of gravity drainage, or specific yield. This report describes one phase of specific yield research by the U.S. Geological Survey's Hydrologic Laboratory in cooperation with the California Department of Water Resources.

An earlier phase of the research concentrated on the final distribution of moisture retained after drainage of saturated columns of porous media. This report presents the phase that concentrated on the distribution of moisture retained in similar columns after drainage for various periods of time.

Five columns, about 4 cm in diameter by 170 cm long, were packed with homogenous sand of very fine, medium, and coarse sizes, and one column was packed with alternating layers of coarse and medium sand. The very fine materials were more uniform in size range than were the medium materials. As the saturated columns drained, tensiometers installed throughout the length recorded changes in moisture tension. The relation of tension to moisture content, determined for each of the materials, was then used to convert the tension readings to moisture content. Data were then available on the distribution of retained moisture for different periods of drainage from 1 to 148 hours. Data also are presented on the final distribution of moisture content by weight and volume and on the degree of saturation.

The final zone of capillary saturation was approximately 12 cm for coarse sand, 13 cm for medium sand, and 52 cm for very fine sand. The data showed these zones were 92 to 100 percent saturated.

Most of the outflow from the columns occurred in the earlier hours of drainage—90 percent in 1 hour for the coarse materials, 50 percent for the medium, and 60 percent for the very fine. Although the largest percentage of the specific yield was reached during the early hours of drainage, this study amply demonstrates that a very long time would be required to reach drainage equilibrium.

In the layered columns the middle (medium sand) layer functioned as a hanging water column accelerating the drainage of the overlying coarse-sand layer. After the middle layer started to drain, the moisture distribution as retained in all three layers showed trends similar to that obtained when the same materials were tested in homogenous columns.

INTRODUCTION

The increasing use of ground water from many major aquifers in the United States has required a more thorough understanding of gravity drainage, or specific yield. Recognizing this need, the California Department of Water Resources and the U.S. Geological Survey began cooperative studies to identify and determine accurately the parameters that are related to and affect specific yield and to perfect more accurate and reliable techniques for laboratory and field determinations of specific yield.

The specific yield of a rock or soil has been defined by Meinzer (1923, p. 28) as the ratio of (1) the volume of water which, after being saturated, the rock or soil will yield by gravity to (2) its own volume. Specific retention represents the water retained against gravity drainage and when added to the specific yield will equal the total interconnected porosity of the rock and soil. Both specific yield and specific retention are usually expressed as a percentage.

SCOPE OF RESEARCH

As the first phase of this study, an annotated bibliography on specific yield and related properties was prepared and released as an open-file report (Johnson, Morris, and Prill, 1961).

To the second phase of the research project—namely, to investigate laboratory methods for determining specific yield—a detailed study was made of the centrifuge-moisture-equivalent and column-drainage methods (Johnson, Prill, and Morris, 1963). Among other results this study showed that the effect of temperature on the centrifuge moisture equivalent was of sufficient magnitude to warrant establishment of a standard temperature for the test (Prill and Johnson, 1959). Also a comparison was made between the centrifuge and the column-drainage techniques (Prill, 1961), and a standard method was developed for packing columns or porous media (Morris and Kulp, 1961). The column-drainage study concentrated on the final distribution of water retained after drainage of saturated columns of porous media.

Another step in the laboratory phases of the research has been a detailed study of moisture tension and centrifuge scale modeling, and reports on these investigations are in preparation. A third and final phase of the research project involves the detailed study of gravity drainage (specific yield) at a number of field sites in California and the evaluation of, and eventual correlation between, laboratory and field methods. The field phases also include detailed studies of the nuclear moisture meter as applied to the determination of changes in moisture content as drainage progresses.

PURPOSE AND SCOPE OF THIS REPORT

This report, which is the second report of the laboratory phase of the research, presents the results of a study of laboratory drainage of columns continued beyond that summarized in the earlier report on column drainage (Johnson, Prill, and Morris, 1963). The scope of this report concentrates on the distribution of water retained in columns of three different sand-size materials after drainage for various periods of time up to approximately 6 days. Both layered and nonlayered conditions are included in this study.

All laboratory work was done in the Hydrologic Laboratory, U.S. Geological Survey, Denver, Colo. The report was prepared under the general supervision of H. D. Wilson and Fred Kunkel, successive district engineer and district geologist of the Ground Water Branch, U.S. Geological Survey, Sacramento, Calif., and under the direct supervision of A. I. Johnson, chief of the Hydrologic Laboratory. The following personnel of the Hydrologic Laboratory assisted with the various laboratory experiments: R. P. Moston, A. H. Ludwig, W. K. Kulp, and N. N. Yabe.

ACKNOWLEDGMENTS

Valuable technical advice was provided by J. F. Poland, research geologist, U.S. Geological Survey in Sacramento, Calif., and V. C. Fishel, district engineer, Ground Water Branch, Lawrence, Kans., who provided useful ideas on the construction of drainage columns.

Many individuals at university and private research laboratories contributed to this report by giving advice and furnishing information relative to the problem. Especially valuable assistance was provided by Mr. R. T. Bean, supervising engineering geologist, and others on the staff of the California Department of Water Resources, Sacramento, Calif.; also Prof. A. T. Corey, Colorado State University, Fort Collins, Colo.

REVIEW OF PREVIOUS WORK

Most methods for obtaining specific yield first require the determination of specific retention. Methods using the drainage of saturated columns of porous media almost universally rely upon the determination of retained moisture. As indicated earlier, the specific yield then may be found by subtracting the specific retention from the total porosity.

During the past 70 years the drainage of columns of porous media has been the subject of many research studies, but very few of these studies have determined the moisture retained in the media after different periods of drainage. A few of these studies are summarized below.

Hazen (1892) presented significant results of tests of the water-retaining and water-yielding capacities of eight different sands used for filtering sewage. These tests related specific yield and specific retention to the effective size and uniformity coefficient as obtained from particle-size analyses.

King (1899) packed five sorted sands of different particle sizes in columns 8 feet in length and 5 inches in diameter. The materials were slowly saturated from below and then drained for 2½ years. Outflow readings were taken during the period of drainage and the moisture content was then determined at the end of the drainage period. The apparatus was designed to prevent moisture loss by evaporation. The results of King's tests showed some discrepancy between the porosity and the total water content and gave lower values for specific retention than Hazen's tests, especially for the coarser samples.

Lebedeff (1927) drained tubes, 4 to 5 cm in diameter and 1 to 3 m in length, filled with sandy soils. A head of water of 2 cm was used to saturate the soil. After drainage, the water retained in 10-cm segments of the column was determined gravimetrically and showed that a uniform moisture content prevailed in the upper part of the columns. The author also saturated 6 pairs of sand tubes 10, 20, 30, 40, 50 and 100 cm high. One tube of each pair was immediately sampled for moisture content. The other tube was allowed to drain until drainage ceased and then sampled to determine the moisture-content distribution throughout the tube. In the longest column, after drainage for 3½ days, the moisture content became constant at a height of about 40 cm. Changing the height of column did not change this distribution; it gave only a longer section of column with constant moisture content. Saturated columns with layers of sand and loess also were drained. More water was retained in the fine-textured material when underlain by coarse-textured material than when underlain by material of the same type.

Stearns, Robinson, and Taylor (1930) collected undisturbed columns of soil in metal cylinders of 18-inch diameter and 36-inch length in the Mokelumne area of California. A bottom was soldered on each cylinder after it was collected, and small-diameter observation wells were installed in each soil column. A water table was established at a high stage in the column. Measured volumes of water were then withdrawn and added alternately and water levels were observed. The time intervals for the water levels to reach equilibrium were very short—only one was over 50 minutes. Greater specific yields were obtained for a rising water table than for a falling water table.

White (1932) collected undisturbed soils in steel cylinders 12 or 18 inches in diameter and 18, 36, or 54 inches long. With the bottom of the cylinders sealed by means of a steel plate, small wells were sunk into the material enclosed within the cylinders. In these wells the effects on the water level produced by adding or withdrawing measured quantities of water were observed. Equilibrium was not established until 24 hours after the addition of water and about 48 hours after its removal. Data indicated the average specific yield for clay and clay loam ranged from about 1 to 7 percent.

Eckis and Gross (1934) packed three 4- by 40-inch cylinders with carefully sorted sand and saturated the columns with a measured quantity of water. Water was then drained from the columns by means of a well attached through a U-tube to the outside bottom of the cylinder. The water table was lowered by slowly removing a measured quantity of water for 1 month, and a period of 30 to 60 days was allowed for the new water table to reach equilibrium. The difference between the water levels was then used to calculate the specific yield. The columns were allowed to drain for an additional 18 months, the cylinders were split, and the moisture contents were determined for 1-inch lengths of column. Evaporation effects were found at depths as great as 27 inches below the top of the columns. Less than 10 percent of the water retained in the column at the end of the 30- to 60-day period drained out in 18 months.

Columns 18 inches in diameter and at least 42 inches long were used by Piper and others (1939) to study specific yield in the Mokelumne area in California. The specific yield was determined by measuring the volume of material saturated or unwatered when measured quantities of water were added or withdrawn from the columns of undisturbed materials. Water levels were affected by both temperature and barometric pressure. No less than 21 days were allowed for a new water level to attain equilibrium and some tests continued for as long as 220 days. The longer drainage periods increased the specific yield by only 1 to 3 percent over that obtained from the short-term drainage. For fine materials, specific yield by saturation was about 3 times as great as that obtained by unwatering, apparently because the columns were too short and were primarily occupied by the capillary fringe. Average values of specific yield obtained were: gravel and coarse sand, 34.8 percent; medium and fine sand, 24.2 percent; very fine sand, silt, and clay, 4.2 percent.

Leverett (1941) used pairs of tubes 10 feet long and of ¾-inch diameter, filled with sand. Sand in one tube of each pair was saturated with water and then allowed to drain for at least 2 weeks whereas the initially dry sand in the other tube was fed water as fast as the sand would imbibe it. His depth-moisture content curves are of the same general character as those of King (1899), but he found that the curves were not the same for the drainage conditions as they were for the imbibition conditions—a hysteresis zone was formed.

Drainage tests of unconsolidated Wilcox sand packed in pipe columns 8 feet long and 2 or 4 inches in diameter were made by Stahl, Martin, and Huntington (1943). The columns were equipped with water jackets to maintain temperature control. Holes were drilled and plugged at 6-inch intervals vertically so cores of the sand could be obtained at any time during drainage. The sand-packed columns were saturated with fluid from the bottom, drained for several hours, and saturated again, prior to each drainage run. Data relating retained moisture to time of drainage were obtained by removing core samples after drainage for given intervals of time. The cavities caused by taking the cores were filled with the fresh sand before the columns were resaturated and drained for a new interval of time. The rate of drainage was found to be proportional to the temperature.

Coleman (1946) packed air-dry clay-loam soil in a brass tube 7 feet long and 6 inches in diameter. Holes were drilled in the tube at 6-inch vertical intervals to provide access for the installation of tensiometers and to obtain samples for moisture content. The column was saturated and drained under a variety of moisture tensions from 0 to 160 cm of water. The proper drainage tension for the soil seemed to be about 125 cm of water, which was equivalent to 19 percent moisture content, the field capacity of the soil.

Gatewood and others (1950) obtained three undisturbed columns of alluvium, each 42 inches in length and 14 inches in diameter. The columns were saturated from the bottom for 15 days, then allowed to drain, and the decline in water level was observed for about 25 days. Water level in the 3 columns reached drainage equilibrium at the end of 9, 10, and 15 days. The volume of water withdrawn from each column was divided by the volume of material unwatered and multiplied by 100 to obtain the coefficient of drainage, in percent, for the period of drainage.

Lambe (1951) drained 2½-inch saturated soil columns with piezometers spaced vertically on the side. They measured and recorded the quantity of outflow and the pressure heads at selected intervals in the column. Pressure heads below the visual line of saturation were measured by piezometers and it was pointed out that the visual line of saturation was not the true line of saturation because a considerable amount of drainage occurred after the visual line of saturation appeared to have reached its equilibrium position.

Terwillinger and others (1951) packed a clean silica sand, by means of mechanical vibration, into a vertical plastic tube 13 feet long and

2 inches in diameter. To eliminate the possibility of boundary flow along the wall of the tubing, the plastic was heated and was forced under pressure to conform to the outside surface of the sand. The column was saturated with a 0.25 normal sodium chloride solution and then allowed to drain. When drainage equilibrium was reached, the saturation distribution was obtained by electrical conductivity readings for probes spaced at 5-cm intervals down the length of the column.

By the use of tensiometers, Luthin and Miller (1953) measured the volume of outflow and recorded the pressure distribution in soil columns, about 8 cm in diameter and 120 cm in length, during drainage. Null-type tensiometers were installed at intervals in the column to determine moisture distribution during drainage of the column. As drainage proceeded, the upper part of the soil column became unsaturated, the water draining until the capillary forces resisting the downward movement of water were sufficient to neutralize the downward forces. The hydraulic gradient approached zero in the lower part of the soil column and the hydraulic conductivity remained high. Water continued to move out of the upper zone under the driving action of a high hydraulic gradient, but movement was slow because of a reduced hydraulic conductivity. Static equilibrium was reached when the hydraulic gradient was zero throughout the column. At this time the soil columns were separated into sections, the moisture content was determined, and the percentage of pore saturation was calculated.

Day and Luthin (1956) did their experimental drainage work with a column of Oso Flaco fine sand, about 87 cm high and 7 cm in diameter. Tensiometers were installed at heights of about 5, 20, 36, 51, 65 and 83 cm from the bottom of the column. The column was saturated, and then drained while the tension and outflow volume measurements were made at selected times. The data were then used to test a numerical solution of a differential equation for vertical flow.

Marx (1956) used a continuous sandstone cylinder, 154 cm long and 5 cm in diameter, with its lateral surfaces sealed in plastic tubing. The volume of water draining from the saturated core was obtained by weighing. The data obtained from the column drainage were compared with drainage data obtained from centrifuging small samples of the same sandstone. The correlation between the two methods seemed to be neither more nor less precise than the sampling technique itself.

Johnson, Prill, and Morris (1963), made a preliminary study of column drainage in which factors such as cleaning of media, method of drainage, column diameter, method of wetting, methods of packing, and length of drainage period were evaluated. They found that cleaning with acid only slightly affected the drainage characteristics for glass beads; that the diameter of the column made little difference in the moisture distribution after drainage of mechanically packed 1-, 4-, and 8-inch-diameter columns of 0.120-mm (millimeter) glass beads; that different procedures for wetting the porous media gave similar results for the distribution of water after drainage and for the rate of discharge; and that a mechanical method of packing produced repeatability of moisture contents.

A theoretical study by Smith (1961) showed that as the meniscus of maximum capillary rise falls through the sand the meniscus enclosing the water bodies retained in draining sand columns is detached from it. The initial drainage under a maximum capillary-rise meniscus accounts for the bulk of the drained water and it is also shown that the data of Hazen (1892) and King (1899) are in good agreement with the developed theory.

The preceding review of the literature shows that in the 60 years or more since the classic experiments of Hazen (1892) and King (1899), relatively little experimental work has been done by hydrologists to determine the specific yield of water-bearing sediments by column-drainage techniques. Many of the controlled experiments that have been completed, both in the laboratory and in the field, have been made by scientists of the agriculture or petroleum-geology disciplines and are not completely applicable to problems of hydrology. The review also indicates that most of the experimental work has been completed on the ultimate drainage, or specific yield, and only a very limited amount of the research has been on drainage obtained for different periods of time. This lack of information and the importance of determining the effect of time on drainage thus provided the impetus for the present study.

THEORY

If a column of porous material is saturated with water and is then allowed to drain to equilibrium conditions, it will be found that the soil column will have retained some water. The amount of water retained in the column of porous media will vary with the height above the water table and with the texture of the media. For media with equal porosities, the smaller the pore spaces the greater will be the amount of retained water.

Three types of soil-moisture distribution—called by Versluys (1917, 1931), the pendular, funicular, and capillary stages—will be found in a column of porous media after it has drained. In the pendular zone, in the upper part of the column of media, the water is retained in rings around the contact points. Lower down in the funicular zone of the column, the rings of water are combined into more complicated forms and are characterized by having two or more contacts embedded in a single mass of water. Near the bottom of the column there is a zone of essentially complete saturation.

Molecular forces tend to arrange the retained water in the pendular zone in the form of small rings around the contact points of the solid particles. These air-water interfaces are convex toward the contact points and must have a curvature that will result in a vapor pressure in equilibrium with the surrounding vapor pressure. Presumably, there will be a thin film of water covering the whole solid particle, but it will not appreciably affect the mass distribution of the water except at a very low water content. A thin film or connecting link of water must exist between the rings of water if the porous media have capillary and electrical conductivity. The experiments by Buckingham (1907) indicated that the soils tested had electrical conductivity for water contents as low as 4 percent by weight.

When a solid water-air system is in stable thermodynamic equilibrium, the vapor pressures have definite values throughout the column of porous media. In other words, the vapor pressures at any two points of equal distance above the water table are equal. According to Kelvin's theorem (Smith, 1933), if two similar masses of liquid are at equal distances above a free liquid, and if one is in communication with, and the other isolated from the free liquid, then not only the vapor pressures over each but the respective curvatures of corresponding parts of each surface are equal. If the curvatures of liquid masses at the same height above a water table are not equal there will be evaporation from one and condensation onto the other until the curvatures become equal. A single isolated liquid mass can therefore be considered as if it were in communication with the water table, so far as transfer of moisture is concerned.

A curved interface between two liquids or between a liquid and a gas indicates that a difference in pressure exists between the two. The difference in pressure, p_c, between a liquid and air is given by the equation

$$p_c=\sigma\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

where σ equals surface tension of the liquid and r_1 and r^2 are the major and minor radii of curvature of the two curves formed by the intersection of two planes at right angles to each other and passing perpendicular through the water surface at the point where it is desired that the curvature be known. If both radii have their centers of rotation on the same side of the interface in question, both radii have the same sign. If the centers of rotation are on opposite sides of the interface, one radius is positive and the other is negative. If we adopt the convention that r_2 is negative, the mean curvature of the air-water interface will be given by

$$\left(\frac{1}{r_1}-\frac{1}{r_2}\right)$$

The difference in pressure at the air-water interface in a capillary tube is equal to γgh where γ is the density of the water, g is the acceleration due to gravity, and h is the height above the water table. According to Kelvin (Smith, 1933), the difference in pressure on the two sides of the air-water interface in the isolated masses of water is also equal to γgh, and thus,

$$p_o=\sigma\left(\frac{1}{r_1}-\frac{1}{r_2}\right)=\gamma gh.$$

We can thus conclude that the curvature of an air-water interface is proportional to its height above the water table. Because the amount of water at each contact point decreases as the curvature increases, the amount of water retained in a column of porous media under equilibrium conditions will decrease with height above the water table.

Smith (1933) analyzed the relation of a free-liquid surface, or water table, to the distribution of soil moisture in an ideal soil under equilibrium conditions. He concluded that the position of the free liquid determines the vapor pressures and curvatures existing in the porous media and also determines the types of distribution zones present. For example, the free-liquid surface may be so far below the bottom of the column of porous media that only the pendular distribution of single rings exists. On the other hand, if the water table is sufficiently close to the bottom of the column, all three distribution zones—pendular, funicular, and saturation—will be present. Thus, the length of the column of porous media is important: it may be so short that it contains only a funicular or saturation zone depending on the relative position of the water table—free-liquid surface.

A brief discussion of tension measurements and relationships is appropriate at this point. If a column of porous material is in equilibrium with a water table and there is no tendency for the water in the media to move either upward or downward, then for each foot of increase in elevation above the water table the tension in the water should increase by an amount equal to 1 foot of water. This relation between the tension and the elevation in the column can be represented (fig. 1) by a straight-line extension upward from the water table with unit slope—that is, 45° if both ordinates are to the same scale. Where the plotted tension readings (negative values) for the tensiometers lie on such a line, it is an indication that hydrostatic equilibrium has been reached or that the hydraulic gradient in the column of

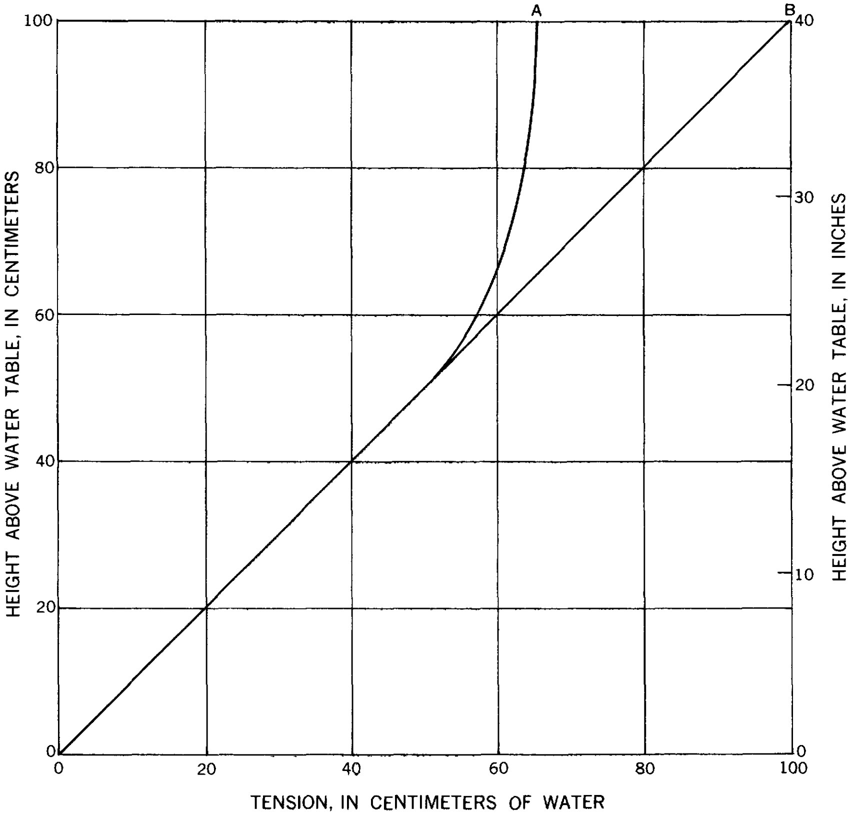

FIGURE 1.—Graph showing relationship of tension to height above water table for a hypothetical sand—in general, the greater the tension the lower the moisture content.

material being drained is equal to the total mechanical potential—the difference in tension between two points, plus the difference in height above the water table for the two points—divided by the length between these points. Line *B* (fig. 1), having a 1-to-1 slope, thus represents a hydraulic gradient of zero or a condition of hydrostatic equilibrium. There is a rapid reduction in unsaturated permeability for sand-size media for a small increase in tension. At the higher tensions, flow may become very slow and may be primarily a function of vapor transfer. In such instances a large increase in tension may correspond to only a very slight decrease in water content.

Although equilibrium drainage is reached when the hydraulic gradient is zero, a hydraulic gradient of close to zero may exist from the water table to several feet above the water table after a relatively short period of drainage of sand-size materials. However, at some distance above the water table, as shown in line *A* on figure 1, the hydraulic gradient may be only slightly less than one and yet all but a fraction of a percent of the total potential yield may have been discharged from the material. If the zero tension intercept of the line *B* is not zero on the depth scale, the intercept value then indicates the elevation of the zero pressure level, or water table, in the soil water.

When the hydraulic gradient is positive, the soil water tends to move downward, whereas when the hydraulic gradient is zero, the soil water is in equilibrium with the water table.

The general principles for operation of a tensiometer are simple. If the water content of the soil decreases, water moves into the soil through the semipermeable tip of the tensiometer. Water then is drawn down in the manometer of the tensiometer system until the pressure difference across the semipermeable tip is balanced by the pressure difference due to the column of water in the manometer tube. In general, the greater the tension in a media, the lower the moisture content.

TECHNIQUES

MATERIALS

One of the prerequisites in the selection of a material to be used in the investigation of moisture distribution with time of drainage was that the material have a capillary rise less than the 170-cm length of columns used in the study. This restricted the materials used in this study to those of the sand- or gravel-size range: glass beads—3M "Superbrite," Minnesota Mining Co., St. Paul, Minn.—of 0.120-mm diameter (very fine sand size); Del Monte sand—DM-20, Del Monte Properties Co., Del Monte, Calif.—of a 20-mesh size (coarse-sand size); and Fresno medium sand—natural sand of medium-sand size collected near Fresno, Calif.—figure 2 shows the particle-size distribution of these materials.

APPARATUS AND CONTROLS

The drainage columns were formed by packing the appropriate media into transparent plastic tubing having an inside diameter of 2.8 cm and a wall thickness of 0.6 cm. The plastic tubing was cut into 2- and 4-cm segments which were calibrated for volume. The segments, with accurately milled end surfaces, were placed end to end and built into leak-proof columns approximately 170 cm in length, by the use of a pressure frame (fig. 3). The bottom segment, containing the outflow tap, was filled with a 80-mesh copper screen for the 20-mesh Del Monte sand and a 230-mesh copper screen for the 0.120-mm glass beads and the Fresno medium sand.

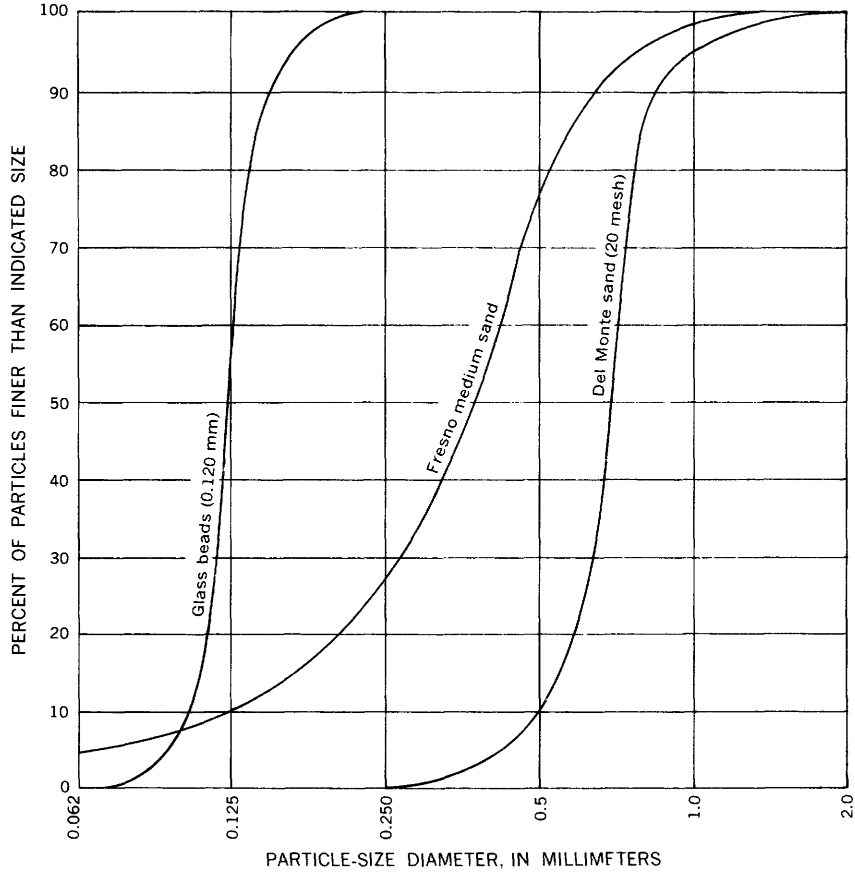

Figure 2.—Particle-size distribution curves of test materials. (See table 1 for values.)

Table 1.—*Distribution of test materials*

[Curves for these values are shown on fig. 2]

Test material	Silt- and clay-size, <0.062	Distribution, in percent, for indicated particle size, in millimeters				
		Very fine 0.062–0.125	Fine 0.125–0.25	Medium 0.25–0.5	Coarse 0.5–1	Very coarse 1–2
Glass beads	--------	52. 2	47. 8	--------	--------	--------
Fresno sand	4. 3	5. 5	17. 3	49. 3	22. 4	1. 2
Del Monte sand	--------	. 1	. 5	9. 6	85. 0	4. 8

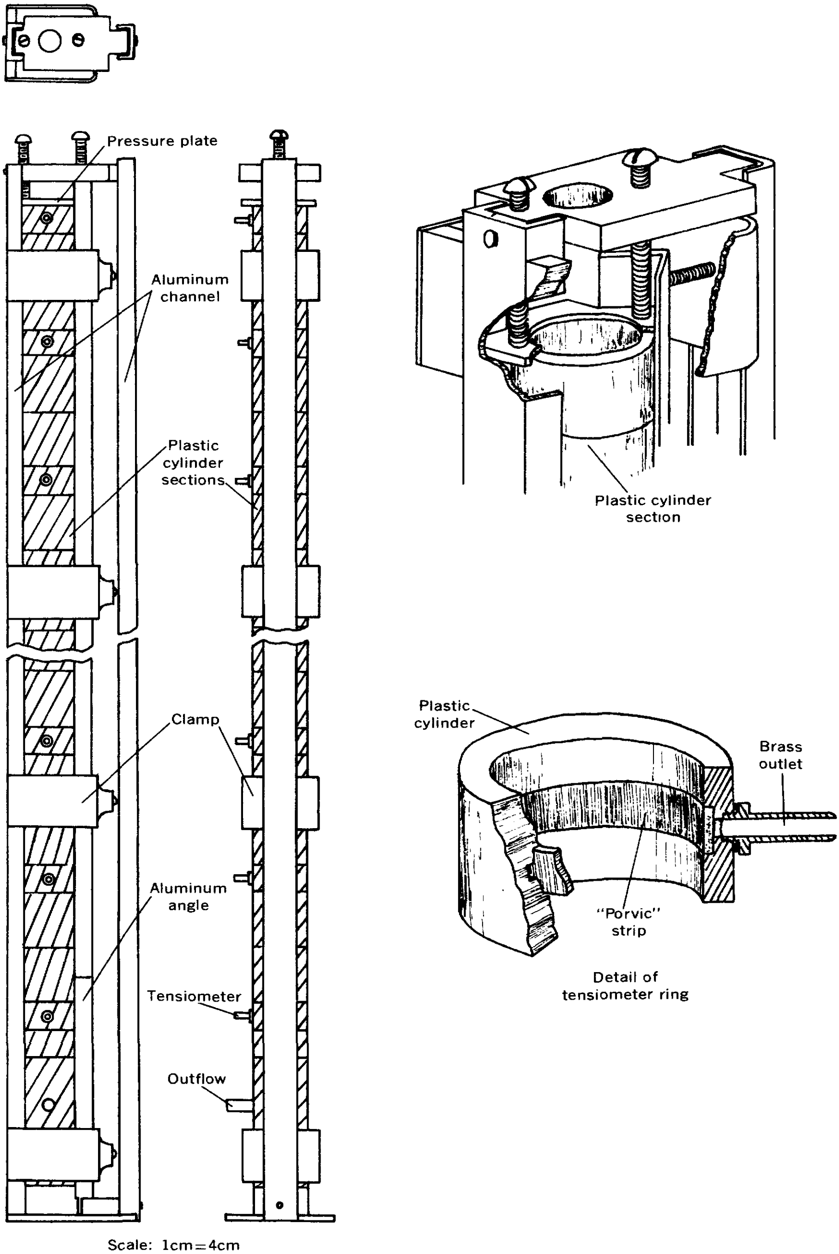

FIGURE 3.—Drawing of assembly for segmented column with ring-type tensiometers.

The water level during drainage was maintained at the base of the column by adjusting a constant-head overflow tank which was connected to the discharge tap.

Tensiometer rings—segments of tubing containing a tensiometer—were placed at appropriate intervals in the column for measuring the tension at selected times of drainage. These ring-type tensiometers were made by gluing strips of a semipermeable plastic sheet ("Porvic" Filter Sheet—Grade "M," Prichett and Gold, London), into 1-cm grooves machined on the inside of 2-cm long plastic segments (fig. 3). The main grooves were machined just deep enough to permit the installation of the "Porvic" flush with the inside wall, but had a deeper groove in the center portion to permit ready movement of water to the outlet tap. A hole was drilled from the outside of the plastic segment to the groove and a brass tap of 0.1 cm inside diameter was threaded into the hole from the outside. Flexible plastic tubing (0.15 cm inside diameter) extended from the tap to the manometers. The "Porvic" plastic, while serving as a barrier to the entry of air into the manometer system, allowed water to move through the system rapidly. Only a short lag thereby occurred between the true tension in the media and the tension recorded by the manometer.

The manometer system is shown in part in figure 4. The manometer tubes in 4- or 8-foot lengths were made of capillary glass of a uniform inside diameter of 1 mm. A water-level change of 128 cm in a manometer would result in a volume change of 1 ml (milliliter). All the tensiometers from one column were connected to the same manometer board. Millimeter graph paper was placed under the manometers so the head in the manometers could be read directly.

The columns were drained in a room where the humidity was maintained at 20 to 45 percent and the temperature was controlled at 20°C. To reduce evaporation, the columns were sealed at the top with cellophane tape through which was a 1-mm hole. In addition, most columns were enclosed within a flexible polyethylene jacket, held together by use of a good nylon-tape fastener, extended from a pan of water immediately below the column to the top of the column and thereby provided an atmosphere having a humidity approximately 10 to 15 percent higher than normal room humidity.

PROCEDURE

CONSTRUCTION AND SATURATION OF THE COLUMN

Prior to constructing a column, the tensiometers were purged of air by first placing them in water that had been boiled and then applying enough vacuum to draw water through the tensiometers and into the flexible tubing. The column was constructed with 2- and 4-cm

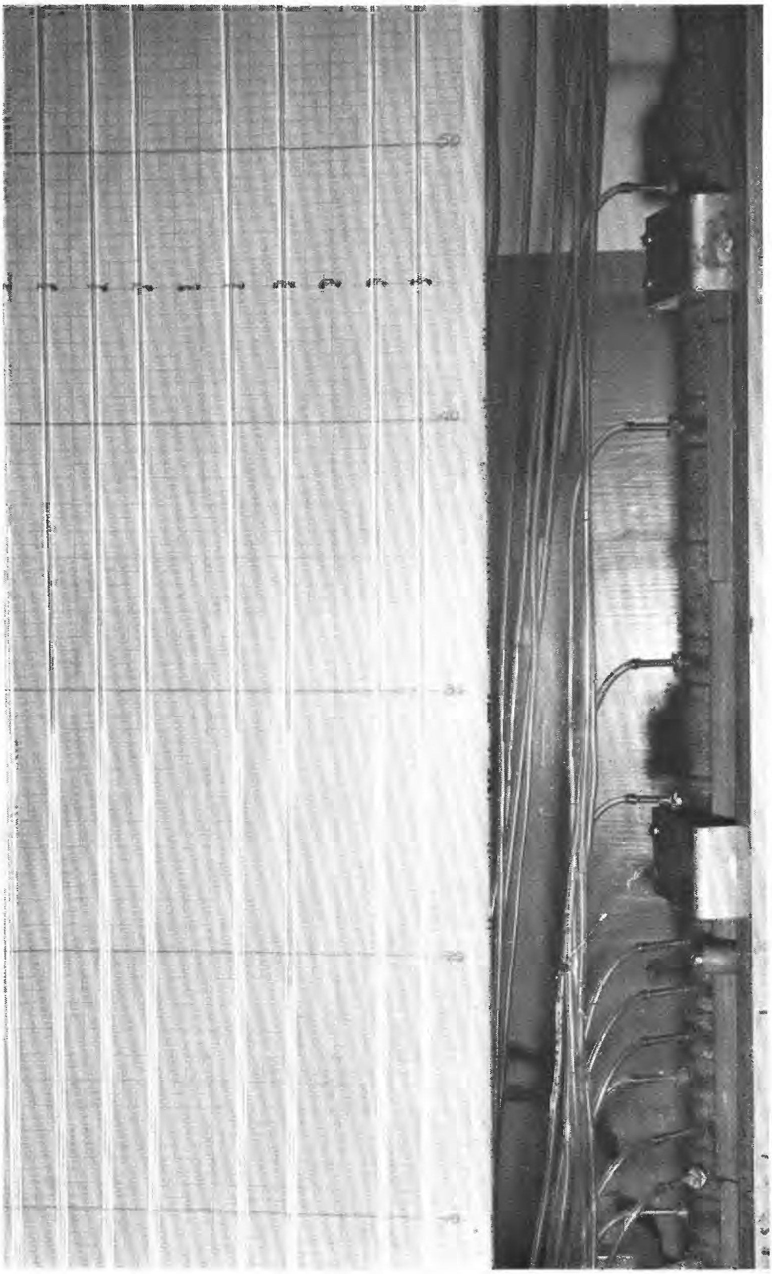

FIGURE 4.—Photograph of tensiometer and manometer system for drainage columns.

segments, placing the 2-cm segments containing the tensiometers at appropriate intervals. The column assembly in the pressure frame was mounted on a vibratory-type packer (Johnson, Prill, and Morris, 1963) and media added by means of a long "tremie" tube.

Unless otherwise noted, all columns packed with a single medium were filled and then vibrated for 10 seconds at a rheostat setting that provided an amplitude of 0.09 cm. For columns containing layers of different media, the column was vibrated after each layer was added.

Deaired Denver tapwater was used as the wetting fluid. (See table 2.) Air was removed from the water by means of a vacuum system especially designed for this purpose. The column was saturated from below by slowly raising the head tank. As the water level in the column reached the level of each tensiometer, the flexible tubing connected with that tensiometer was attached to the appropriate manometer on the manometer board. Water was allowed to move up each manometer to a preselected level based on an estimate of the tension that would exist for that manometer after one-half hour of drainage. The flexible tubing was then pinched with a hose clamp to prevent any further upward movement. The total wetting period for a column was approximately 65 hours.

TABLE 2.—*Chemical analysis of water from Denver, Colo.*

[Analysis by Quality of Water Laboratory, U.S. Geol. Survey, Denver, Colo.]

Constituent	Concentration (ppm)
Calcium (Ca)	20
Magnesium (Mg)	4
Sodium (Na) and potassium (K)	3.4
Bicarbonate (HCO_3)	47
Sulfate (SO_4)	31
Chloride (Cl)	1.5
Fluoride (F)	.2
Nitrate (NO_3)	.6
Dissolved solids	99
Hardness (as $CaCO_3$)	66
Specific conductance, micromhos at 25° C	161
pH	7.3

DRAINAGE AND SAMPLING OF THE COLUMN

Drainage was started by allowing water to discharge through the lower head tank as the water level was maintained at the base of the column. The zero reference point of the graph paper on the manometer board was placed at the same level as the base of the column and the height above zero measurement was scaled off in centimeters. At the start of drainage the hydraulic head at any location in the media would be equal to the distance from that location to the top of the column. During drainage, manometer and accumulated discharge readings were recorded frequently. Manometer readings were converted to tension readings by subtracting the manometer reading—minus a correction for capillary rise in the manometer tube—from the height of the tensiometer above the water table.

During the early minutes of drainage there was a noticeable lag in manometer readings caused by rapid change from positive to negative head values. After 1 hour of drainage, the rate of change in manometer readings reduced considerably and there was no noticeable lag. Because of the lag in early manometer readings, tension values were not reported usually until after 1 hour of drainage.

After drainage the pattern of moisture distribution and the dry unit weight throughout the column were determined. The pressure on the segments of the drainage column was released and the porous medium was removed and weighed as the segments were separated one by one from top to bottom of the column.

DISCUSSION OF TEST RESULTS

The procedures used in the drainage studies were generally the same for all drainage tests. One drainage test was made using 0.120-mm glass beads and 2 drainage tests each were made using 20-mesh Del Monte sand and Fresno medium sand. In addition, one drainage test was made of a column of layered media composed of layers of 20-mesh Del Monte sand and Fresno medium sand.

A wide variety of data was obtained on the moisture and physical properties of the porous media during or following drainage of the columns. Dry unit weight was determined by the following equation:

$$\gamma_d = \frac{W_s}{V_s}$$

where

γ_d = dry unit weight, in grams per cubic centimeter;
W_s = weight of over-dry sample in segment, in grams;
V_s = volume of sample in segment, in cubic centimeters.

Specific gravity of solids (absolute), G, is the ratio of the unit weight of the solid particles (grain density) to the unit weight of distilled water at 4°C.

The volumetric-flask method was used for determining specific gravity. The sample was disaggregated into individual particles and a weighed oven-dry portion was placed in water in a calibrated volumetric flask. The volume of the particles was equivalent to the volume of displaced water. The unit weight of the solid particles was obtained by dividing the dry weight of the sample by the volume of the solid particles. As the density of water at 4°C is unity in the metric system, the specific gravity is numerically equivalent to this unit weight.

Porosity was determined by the following equation:

$$n=\frac{\gamma_s-\gamma_d}{\gamma_s}(100)$$

where

n=porosity, in percent;

γ_s=average unit weight of solid particles (numerically equal to specific gravity of solids in metric units), in grams per cubic centimeter.

The moisture content by dry weight is defined as the ratio of (1) the weight of water contained in a sample to (2) the oven-dry weight of solid particles, expressed as a percentage. Moisture content by volume was determined by multiplying the moisture content by weight by the dry unit weight (γ_d), expressed as a percentage. The degree of saturation, expressed as a percentage, was determined by dividing the moisture content (percent of volume) by the porosity (in percent).

Measurements of outflow during drainage were plotted as accumulated outflow in milliliters against time of drainage in hours. Flow into or out of the media from the manometer during drainage was determined by subtracting the manometer readings, after selected intervals of drainage, from the readings at the start of the experiment. The total change in manometer readings in centimeters was then divided by 128 to give the computed flow in milliliters (128 cm length on manometer equals 1 ml volume).

Tension after selected periods of drainage was plotted against height above water table. Time periods were selected to represent nearly equivalent changes in the period. Tension readings taken just prior to segmenting the column were compared to the moisture content after drainage of the appropriate tensiometer segment and these values were used for developing a curve relating moisture content to tension. Tension values measured during the drainage tests were then converted to moisture contents and plotted against height above the water table. A pictorial estimate of the distribution of water above the water table after selected periods of drainage thus could be obtained.

DRAINAGE OF 0.120-MILLIMETER GLASS BEADS

A single drainage test was run using a column of 0.120-mm glass beads. The vertical thickness of the media was 171 cm and the period of drainage was 99 hours.

TENSION IN RELATION TO TIME OF DRAINAGE

The data shown in figure 5 indicate the pattern of tension distribution over the period of 99 hours of drainage. Tension increased—

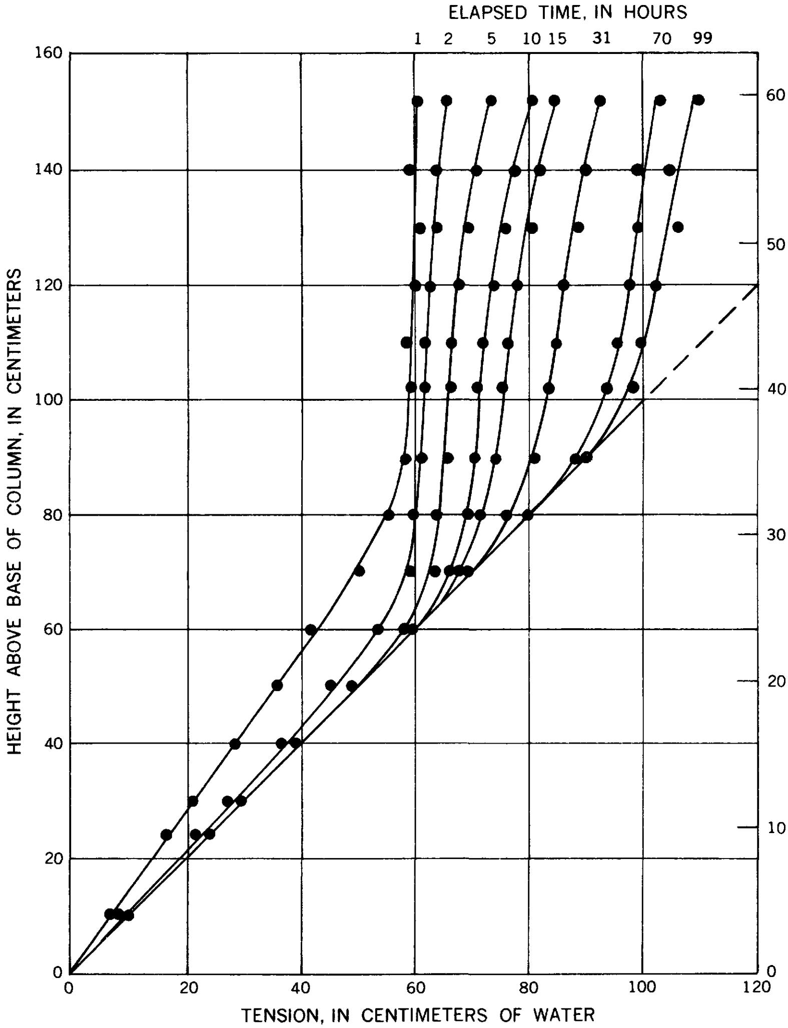

FIGURE 5.—Graph showing tension distribution during drainage of 0.120-millimeter glass beads.

moisture content decreased—very rapidly in the early hours of drainage and after 5 hours reached in the lower 60 cm of the column a value approximately equal to the height above the base of the column. The hydraulic gradient—computed from the tension data—in this lower part of the column was approximately three-tenths by the end of 1 hour, one-tenth after 2 hours, and close to zero after 5 hours of drainage.

The vertical distance from the base of the column to the point where the hydraulic gradient was close to zero increased with time and reached about 90 cm at the end of the 99-hour drainage period.

In the upper part of the column after 1 hour of drainage the hydraulic gradient was close to one. The gradient decreased with time of drainage, being approximately seven-tenths at the end of drainage. Tension in this upper section of the media decreased at a gradually diminishing rate during the period of drainage. However, at the time the beads were sampled for moisture content, the rate of change of tension with time of drainage had reached a very low value.

The progressive decrease in rate of change in tension with increased time of drainage suggests that a period of drainage much longer than 4 days would be necessary before a hydraulic gradient of zero (or hydrostatic equilibrium) would exist throughout the vertical section of the beads. However, the percentage of the total discharge that would occur in the upper section of the columns after 4 days of drainage would be very small. This decrease in rate of change in tension during the later period of drainage indicates that 1 or more years of time would be required before a hydraulic gradient of zero would exist throughout the column. The principal change in tension probably would be caused by vapor transfer, although it is reported to be a very slow process (Richards and Moore, 1952) in comparison to film transfer.

PHYSICAL AND HYDROLOGIC PROPERTIES AFTER DRAINAGE

Figure 6 shows the vertical distribution within a column of 0.120-mm glass beads of the dry unit weight and porosity after drainage. Figure 7 shows the moisture retained after drainage. As shown in figure 6, dry unit weight and porosity varied over a narrow range throughout the column of beads. The average dry unit weight was 1.47 g per cc and the range was from 1.44 to 1.50. The average porosity was 41.2 percent and the range was from 40.0 to 42.4.

The plot of vertical distribution of moisture content and the degree of saturation (fig. 7) show that the zone of capillary saturation, or near saturation, for the glass beads extended to a height of 53 cm. This zone has a moisture content of approximately 38 percent of volume and was approximately 92 percent saturated. The degree of saturation decreased rapidly above 53 cm to a value of 6 percent in the upper part of the column. Except for a sharp decrease in moisture content at the top segment, probably caused by evaporation, essentially no change occurs at heights above 100 cm that have a moisture content of approximately 3 percent of volume.

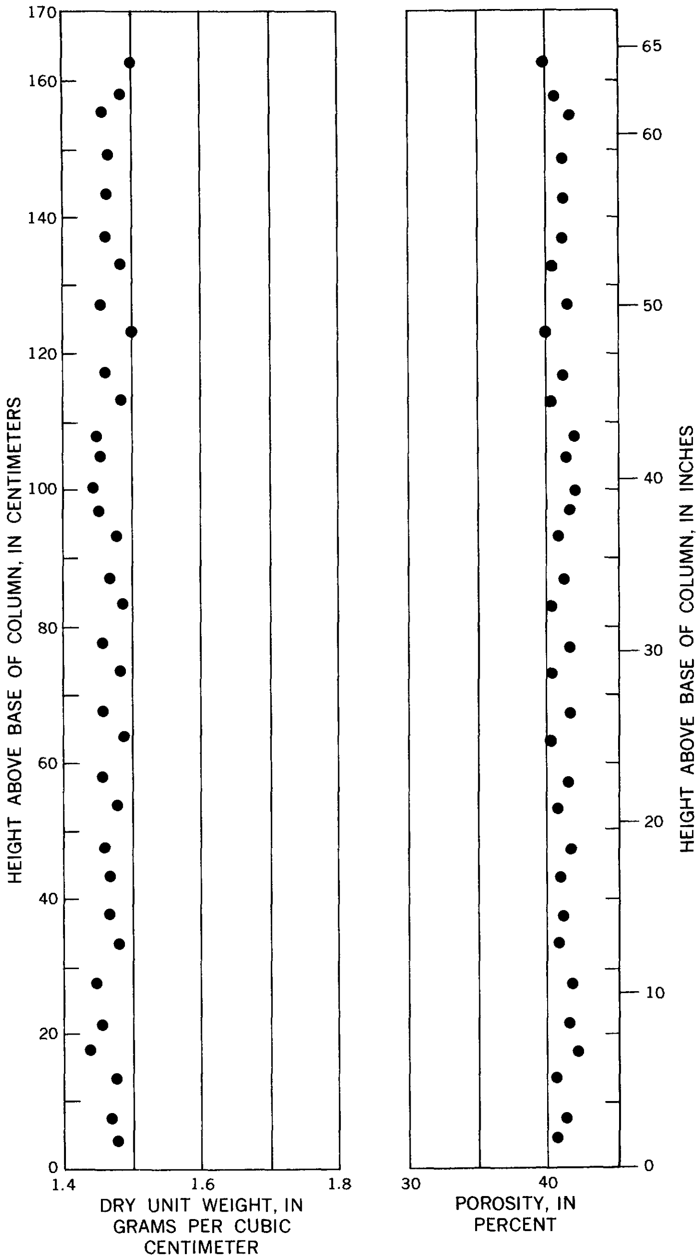

FIGURE 6.—Graph showing distribution of dry unit weight and porosity after draining a column of 0.120-millimeter glass beads.

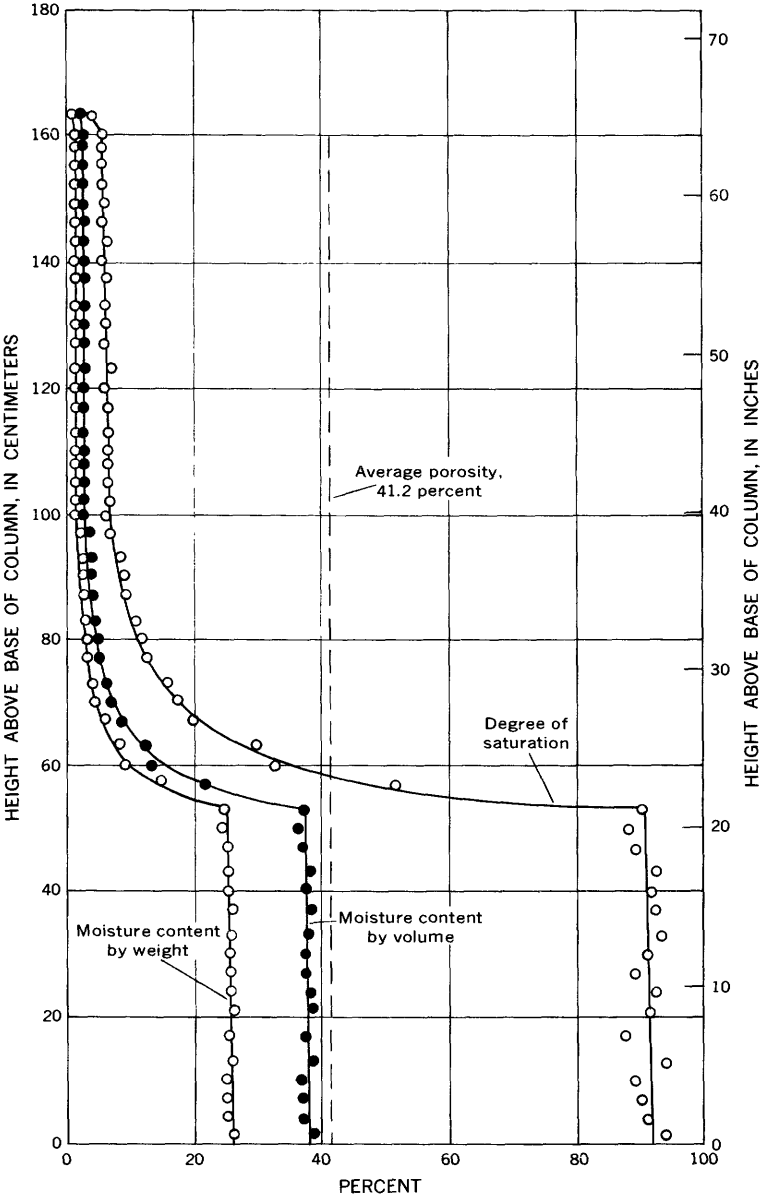

FIGURE 7.—Graph showing moisture retained after drainage of 0.120-millimeter glass beads.

The curve shown on figure 8 relates moisture content to tension. The points for this curve were obtained by recording the tension values at the end of the 99-hour drainage period and then determining moisture content of the beads in the segments. In addition to using the moisture and tension values of the beads in the segments containing tensiometers, the moisture and estimated tension values of the beads in all segments below 85 cm from the base of the column were used. The estimated tension values in this lower section of the column were considered to be equal to the height above the base of the column (see fig. 5). The equilibrium moisture content in the tension zone above 100 cm of water is 2.5 percent of volume.

MOISTURE DISTRIBUTION AND DISCHARGE IN RELATION TO TIME OF DRAINAGE

Using the moisture-tension curve (fig. 8), the tension data (fig. 5) were converted to moisture content. The data indicating the pat-

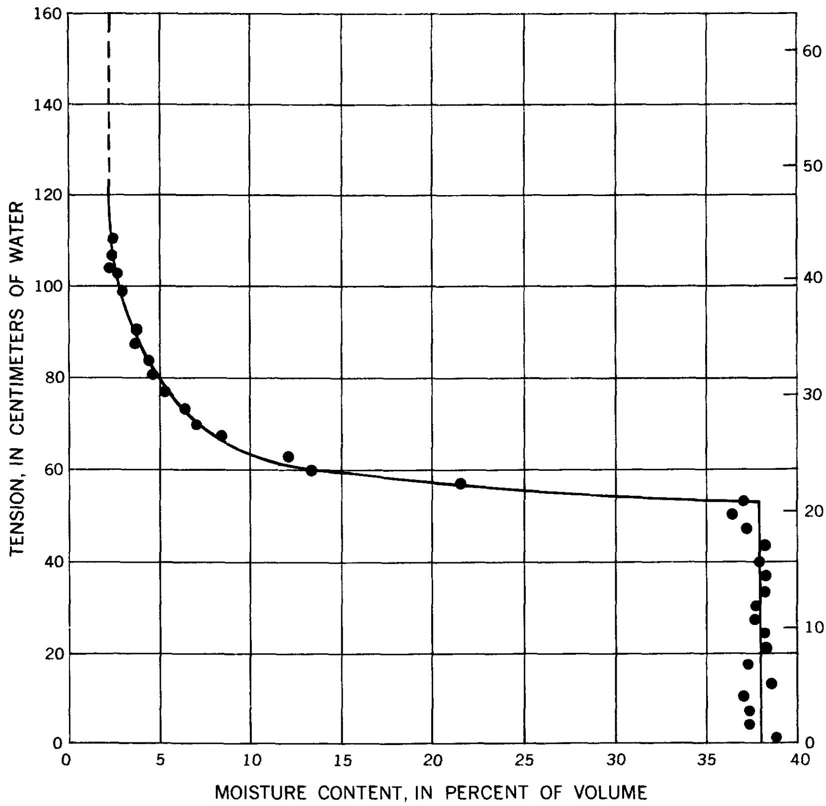

FIGURE 8.—Graph showing relation of moisture content to tension for 0.120-millimeter glass beads.

tern of water distribution over a period of 99 hours of drainage are shown on figure 9. The discharge of water in relation to time of drainage is shown on figure 10.

The accumulated discharge includes an estimated volume of 5.5 ml contributed by the manometer system. The outflow data provide a direct measurement of the accumulated discharge from the column and the moisture-distribution curves provide an indirect measurement of discharge and indicate the point of discharge in the column. After 1 hour of drainage, approximately 60 percent of the total discharge had occurred; after 5 hours, approximately 90 percent; and after 15 hours, approximately 97 percent. Although no measurable outflow occurred between 70 and 99 hours, the moisture-distribution curves indicate a very slight decrease in moisture content in the upper half of the column over this same period of time. Figure 5 shows a change in tension values of from 4 to 7 cm of water between the period of 70 and 99 hours of drainage. At the higher tensions there

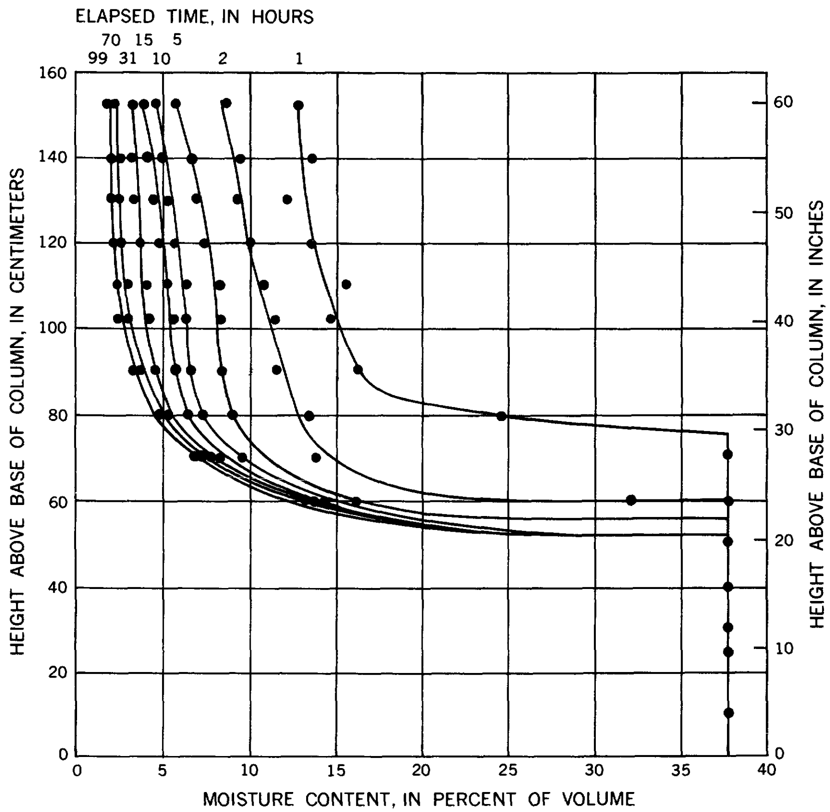

FIGURE 9.—Graph showing moisture distribution during drainage of 0.120-millimeter glass beads.

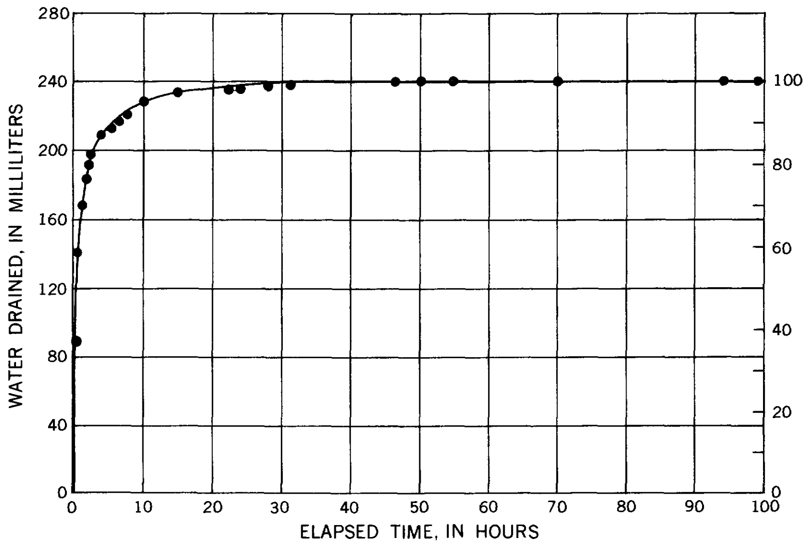

FIGURE 10.—Graph showing quantity of water drained from a column of 0.120-millimeter glass beads as related to time of drainage.

is a very small change in moisture content with a large change in tension (fig. 8). This suggests that although hydrostatic equilibrium was not obtained in this test, the outflow between this time and that when the drainage was terminated would be a small fraction of a percent of the total drainage. Results obtained and observations made during the tests indicated that very precise controls would need to be employed in order to obtain reliable data for hydrostatic equilibrium. These would include humidity controls that would insure that there was no evaporation from the column, the outflow system, or from the manometers, and temperature controls of a very precise nature to insure against temperature gradients being developed in the media.

DRAINAGE OF FRESNO MEDIUM SAND

Two drainage tests were run using Fresno medium sand. In the first test the column was filled with sand and mechanically packed as described earlier. After settling by vibration, the level of the sand was 148 cm above base of column. Sand was added in increments of 5 cm and manually packed, by tapping each addition with a rubber-padded stick, to a level of 163 cm. The porosity in the hand-packed section was found to be less than that in the section of column that was packed by vibration.

In the second test the column was filled with sand and mechanically packed only. The vertical thickness of the sand after vibration was

150.5 cm. The drainage period for the first test was 148 hours and for the second was 94 hours.

During drainage of column 1 the temperature-control unit became inoperative and the temperature increased to 25°C.

TENSION IN RELATION TO TIME OF DRAINAGE

The data shown on figures 11 and 12 indicate the pattern of tension distribution in the sand during drainage of columns 1 and 2, respectively. Although the two columns of sand were not comparable in vertical thickness, the general pattern of tension distribution with time of drainage is quite similar.

Tension increased very rapidly during the early hours of drainage, approaching a hydraulic gradient close to zero after 4 hours in the lower 25 cm of the columns of sand. The vertical thickness of media having a hydraulic gradient near zero increased with increased time of drainage, becoming about 45 cm after nearly 48 hours of drainage and 60 cm in column 1 after about 148 hours of drainage. In the upper part of the columns the change in tension decreased with time and had reached a very low rate at the time the sand was sampled for moisture content and porosity. The hydraulic gradient decreased from slightly less than 1 after 1 hour of drainage to seven-tenths after 96 hours of drainage.

PHYSICAL AND HYDROLOGIC PROPERTIES AFTER DRAINAGE

Figures 13 and 14 show, for both columns 1 and 2 of Fresno sand, the distribution of dry unit weight, porosity, moisture content, and degree of saturation at various heights above the base of the column. Dry unit weight and porosity were not determined in the segments below 25 cm where a number of sand grains remained on the inside wall of each segment after the bulk of the sample had been removed. Because the moisture contents would have been affected by evaporation, these sand grains were not removed.

As shown on figure 13, the vertical distribution of dry unit weight and porosity for the two drainage columns had similar trends. The values are similar throughout the sections of the columns between 75 and 150 cm, but between 25 and 75 cm there is a trend towards an increase in dry unit weight and decrease in porosity with height above the base of the column. The average dry unit weight and porosity were 1.71 g per cc and 36.7 percent, respectively, for column 1, and 1.70 g per cc and 37.0 percent for column 2.

The vertical distribution of moisture content and the degree of saturation for columns 1 and 2 are plotted in figure 14. The data show that the moisture content and the degree of saturation have similar trends for the two columns. Because no porosities were available

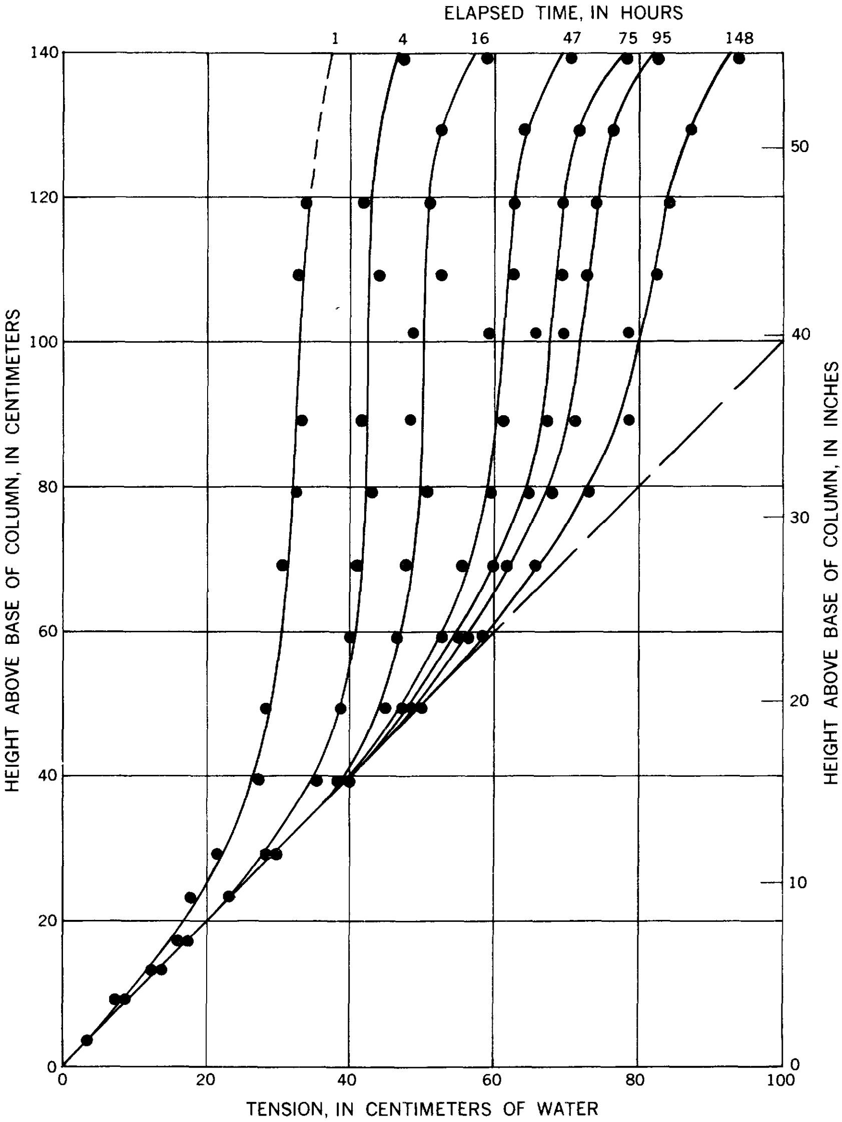

FIGURE 11.—Graph showing tension distribution during drainage of Fresno medium sand (column 1).

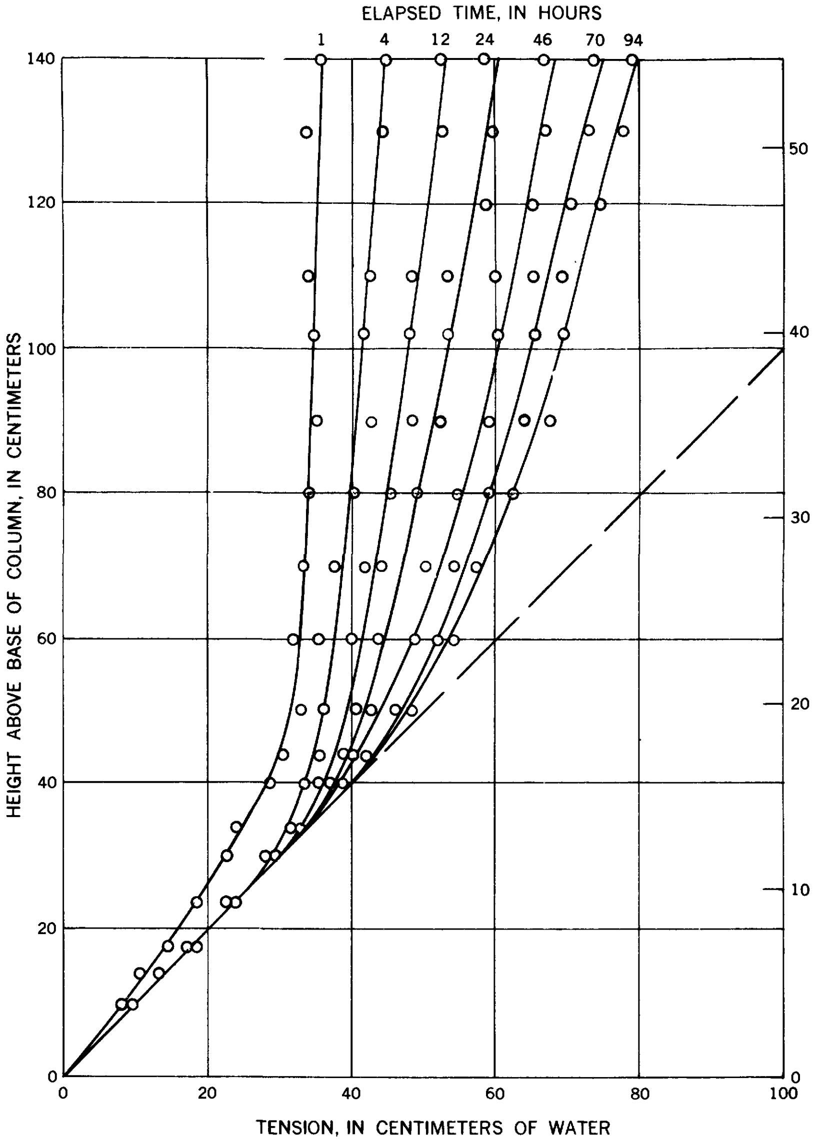

FIGURE 12.—Graph showing tension distribution during drainage of Fresno medium sand (column 2).

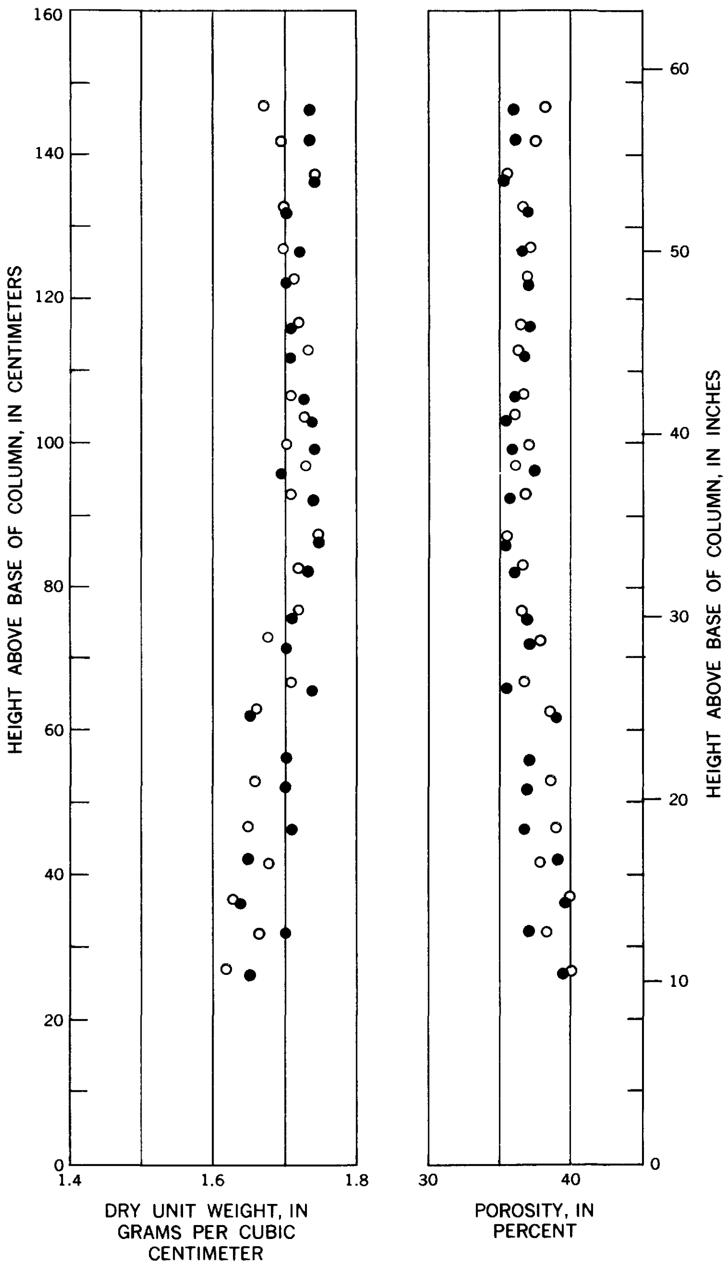

FIGURE 13.—Graph showing distribution of dry unit weight and porosity after draining columns of Fresno medium sand. Solid circles refer to column 1; open circles refer to column 2.

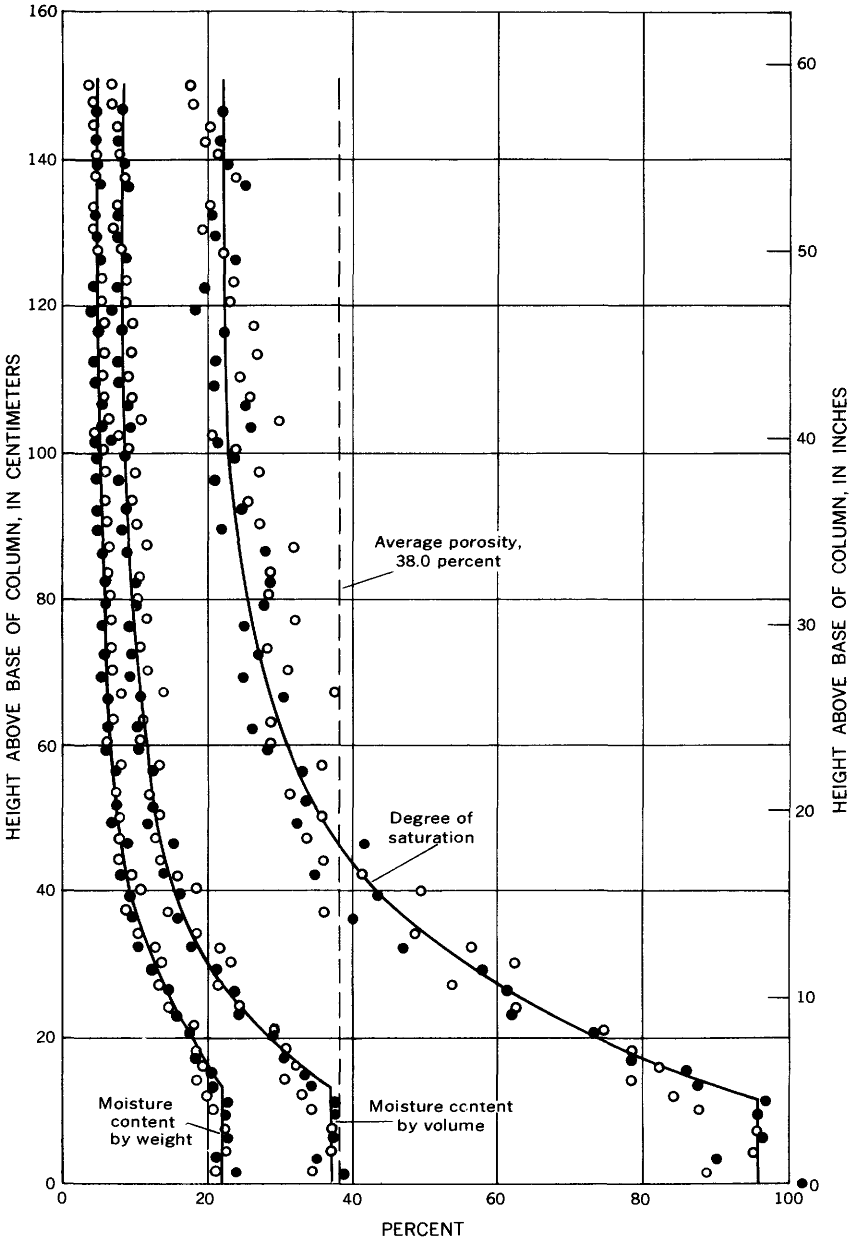

FIGURE 14.—Graph showing moisture retained after drainage of Fresno medium sand. Solid circles refer to column 1; open circles refer to column 2.

for the lower sections of the columns, the degree of saturation in those sections was obtained by using average porosities.

The zone of capillary saturation extends from the base of the column to a height of approximately 12 cm. The average degree of saturation in this zone was calculated to be approximately 96 percent for column 1 and 92 percent for column 2. Because these values were calculated using average porosity values, the resultant degree of saturation will represent only approximate values. The average moisture content for both columns in this zone is approximately 22 percent by weight and 37 percent by volume.

The degree of saturation decreased with increasing height above 12 cm, with the rate of decrease being less pronounced than for the 0.120-mm glass beads. In the section of the column above 110 cm, the degree of saturation was essentially constant, at 22 percent.

The curve relating moisture content to tension for Fresno medium sand is shown in figure 15. The hydraulic gradient at the end of drainage was nearly zero in the vertical section of the column below 60 cm for test 1 and 45 cm for test 2. Because the tension values are virtually equal to the heights of the tensiometers above the base of the column, the moisture values in these sections were used in forming the calibration curve.

The points from which the moisture-tension curve was extrapolated are more scattered than the points for 0.120-mm glass beads. This wide scatter is probably due to the more heterogeneous nature of the Fresno sand (fig. 2) and the difficulty of constructing a column of Fresno sand that would have a uniform distribution of particle size.

MOISTURE DISTRIBUTION AND DISCHARGE IN RELATION TO TIME OF DRAINAGE

Using the moisture-tension curve (fig. 15) the tension data (fig. 11 and 12) were converted to moisture content in percent of volume. The moisture content data are shown in figure 16 for test 1 and figure 17 for test 2.

The change in moisture content for tests 1 and 2 from 75 hours of drainage to the time the columns were segmented was very small, yet, there was an appreciable change in tension over this period of time.

As experienced in the drainage of the 0.120-mm glass beads, hydrostatic equilibrium was not obtained in either of the two drainage tests of Fresno medium sand. However, here also, all but a small part of the total potential drainage appeared to have occurred during 4 days of drainage.

The accumulated discharge compared with time of drainage for tests 1 and 2, shown in graph form in figure 18, was 50 percent of the total discharge after one hour of drainage, 75 percent after 4 hours

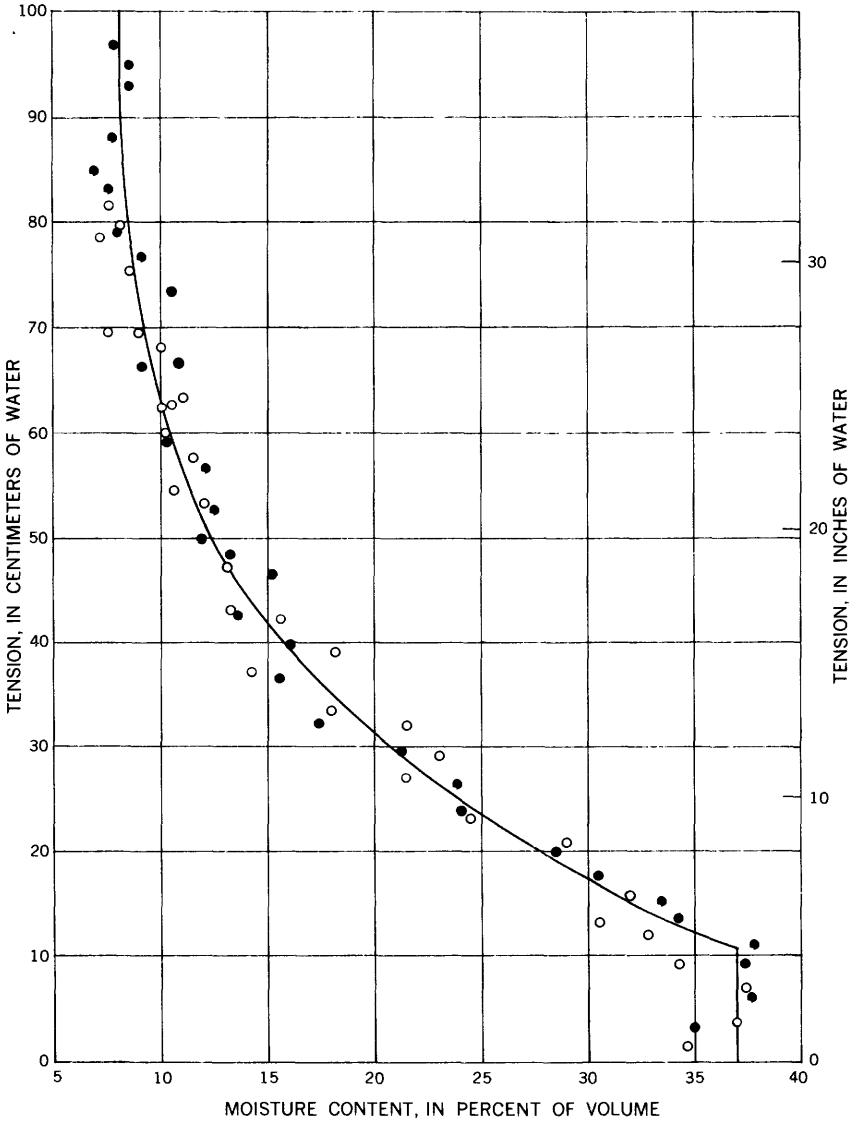

FIGURE 15.—Graph showing relation of moisture content to tension for Fresno medium sand. Solid circles refer to column 1; open circles refer to column 2.

of drainage, 90 percent after 24 hours, and over 99 percent after 75 hours of drainage. The reasons for the differences in total discharge of the two columns are (1) the different vertical thicknesses of column, and (2) a difference in outflow from the manometer systems.

DRAINAGE OF 20-MESH DEL MONTE SAND

Two drainage tests were made using 20-mesh Del Monte sand. The vertical thicknesses of the columns were 152 cm and 148 cm respectively. The period of drainage for each test was 28 hours.

TENSION IN RELATION TO TIME OF DRAINAGE

Figures 19 and 20 show the tension distribution during drainage for columns 1 and 2, respectively. In the two tests, essentially no change in tension at distance of less than 20 cm above the base of the column was observed over the drainage period of 1 to 28 hours.

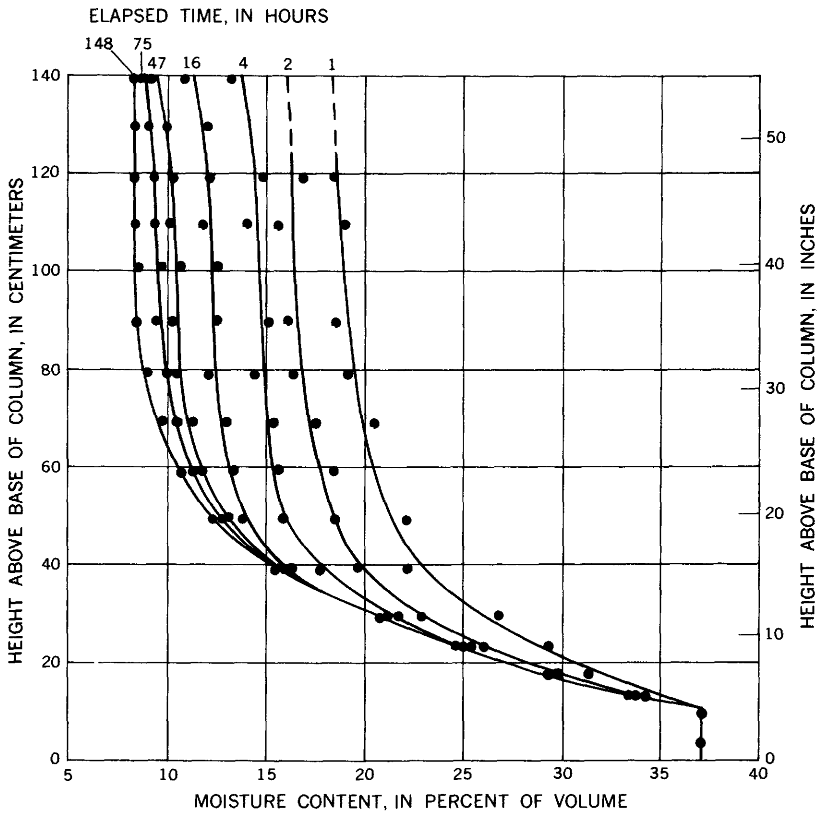

FIGURE 16.—Graph showing moisture distribution during drainage of Fresno medium sand (column 1).

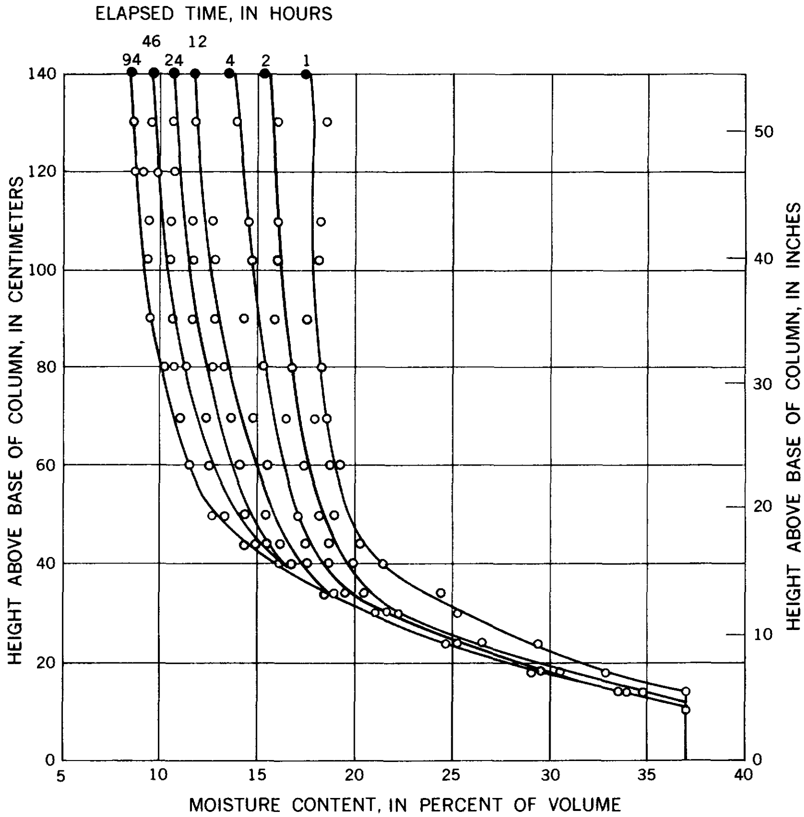

FIGURE 17.—Graph showing moisture distribution during drainage of Fresno medium sand (column 2).

Even at heights of over 30 cm above the base of the column, the change in tension was, in general, slightly less than 10 cm—the maximum change in tension at any tensiometer location over this period being 11.1 cm. Because of the small change in tension in the upper part of the columns, all tension readings above 30 cm for each selected time period were used to extrapolate the time-tension trend lines (figs. 19 and 20). Thus, these trend lines smooth out the effects of contact with media, differences in manometer diameter, changes in porosity of media, and other factors that cause variations in the readings of the tensiometers.

At the end of 1 hour of drainage, the hydraulic gradient in the two tests approached zero in the lower 22 cm of the columns and was close to one above 22 cm. After 28 hours of drainage the hydraulic gradient was nearly zero in the lower 28- to 29-cm section of the column and was close to one above this height. During the last 16 hours of drainage the change in tension above a vertical height of 28 cm was about 2 cm of water.

PHYSICAL AND HYDROLOGIC PROPERTIES AFTER DRAINAGE

Data in figures 21 and 22 give the vertical distribution of dry unit weight, porosity, moisture content, and degree of saturation with heights above the base of the column for the two columns of 20-mesh Del Monte sand. As shown in figure 21, dry unit weight and porosity changed very little throughout the column. The average dry unit weight was 1.71 g per cc for test 1 and 1.73 g per cc for test 2, and the average porosity was 35.5 percent for test 1 and 34.7 percent for test 2.

The vertical distribution of moisture content and the degree of saturation (fig. 22) show that the zone of capillary saturation extends from the base of the column to a height of about 10 to 12 cm. Only one porosity value was obtained in this zone because tensiometers were concentrated in the lower section of the columns. Using this porosity, the degree of saturation was calculated to be 96.5 percent. All other calculations for degree of saturation in this section of the column were made using the average porosity in the column. The degree of saturation was found to range from 95 to slightly greater than 100 percent, the values greater than 100 percent probably resulting from use of the average porosity in the calculations of saturation.

Above the zone of capillary saturation the degree of saturation in the Del Monte sand decreased sharply to 12 percent, this decrease being

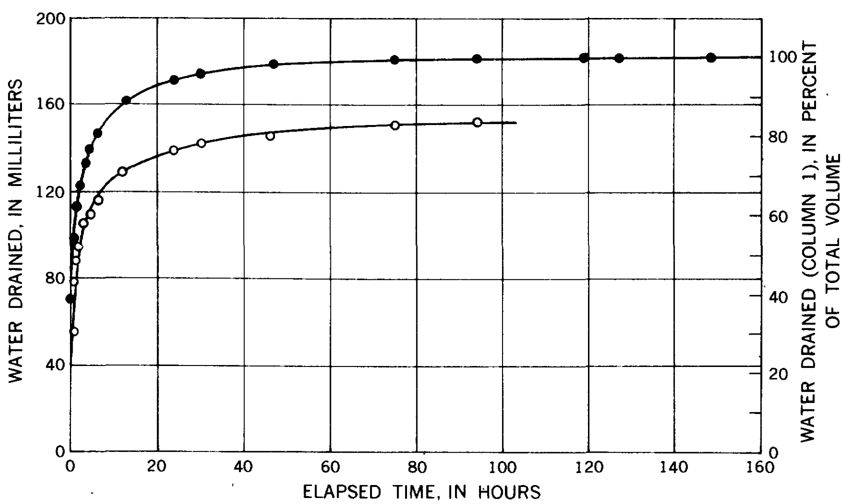

FIGURE 18.—Graph showing quantity of water drained from columns of Fresno medium sand as related to time of drainage. Solid circles refer to column 1 (163.2 cm long); open circles refer to column 2 (150.5 cm long).

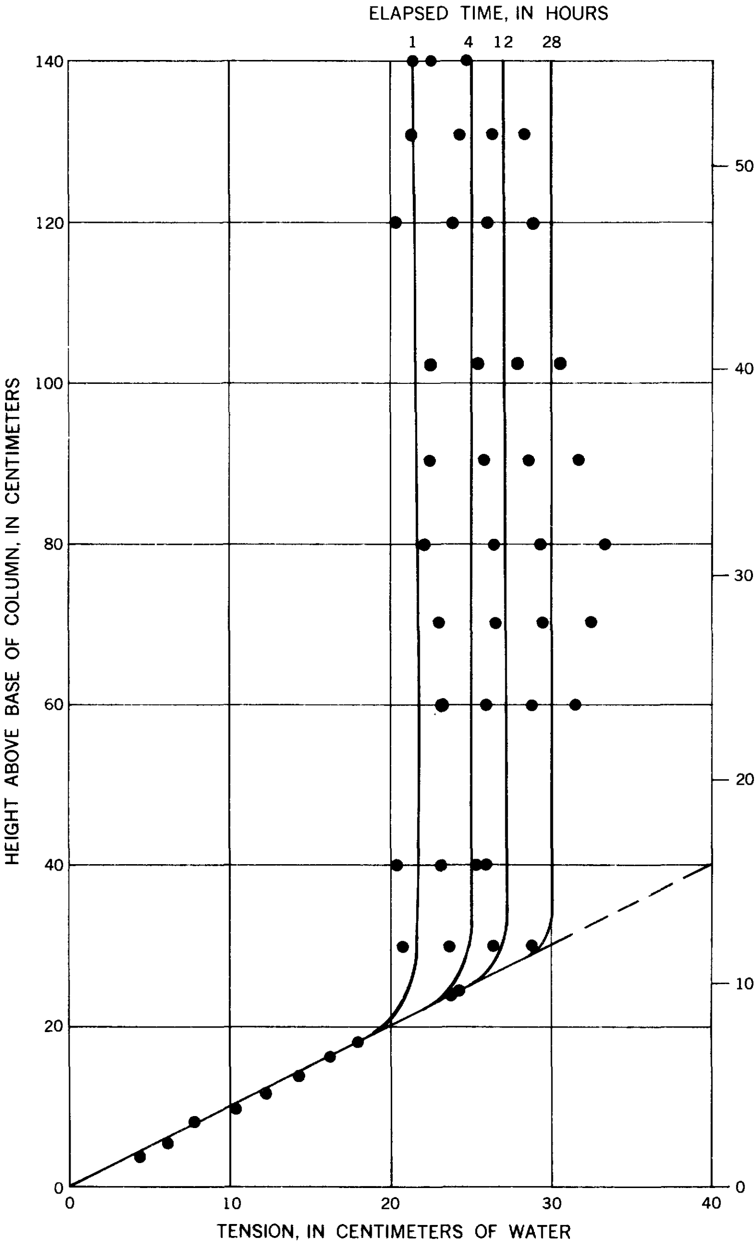

FIGURE 19.—Graph showing tension distribution during drainage of 20-mesh Del Monte sand (column 1).

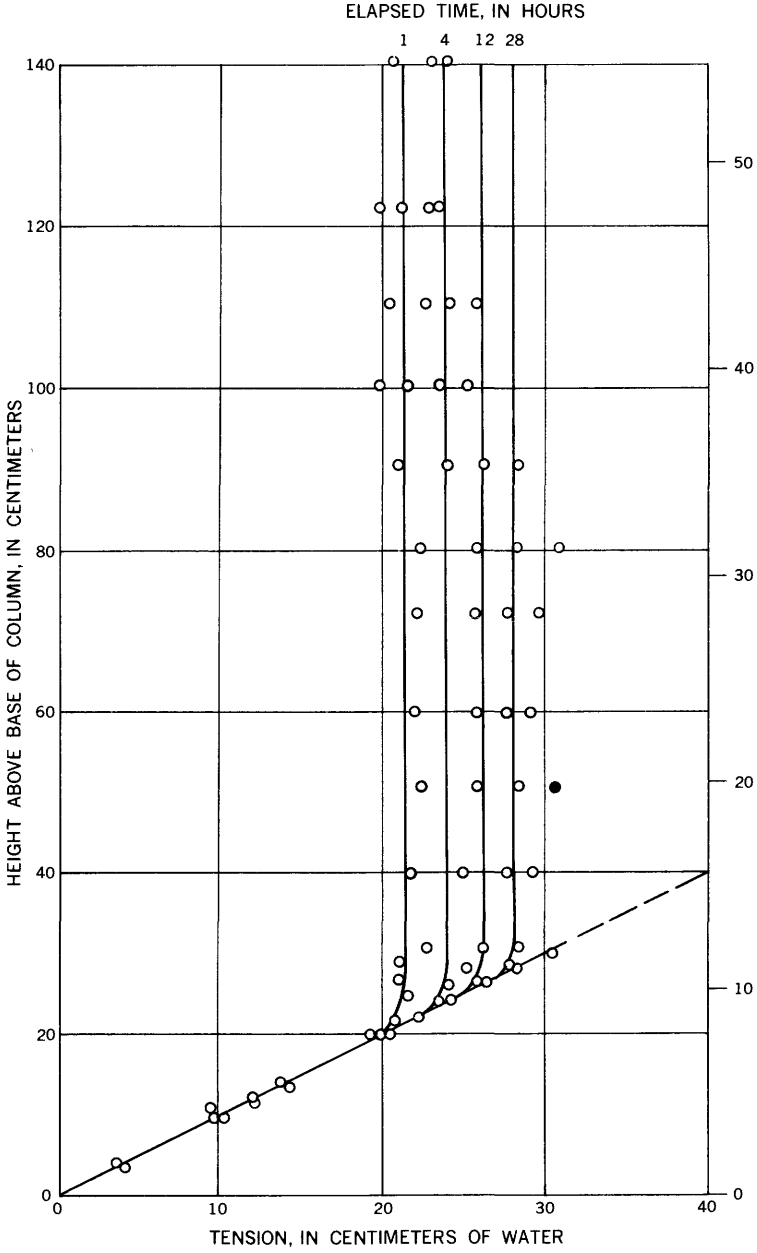

FIGURE 20.—Graph showing tension distribution during drainage of 20-mesh Del Monte sand (column 2).

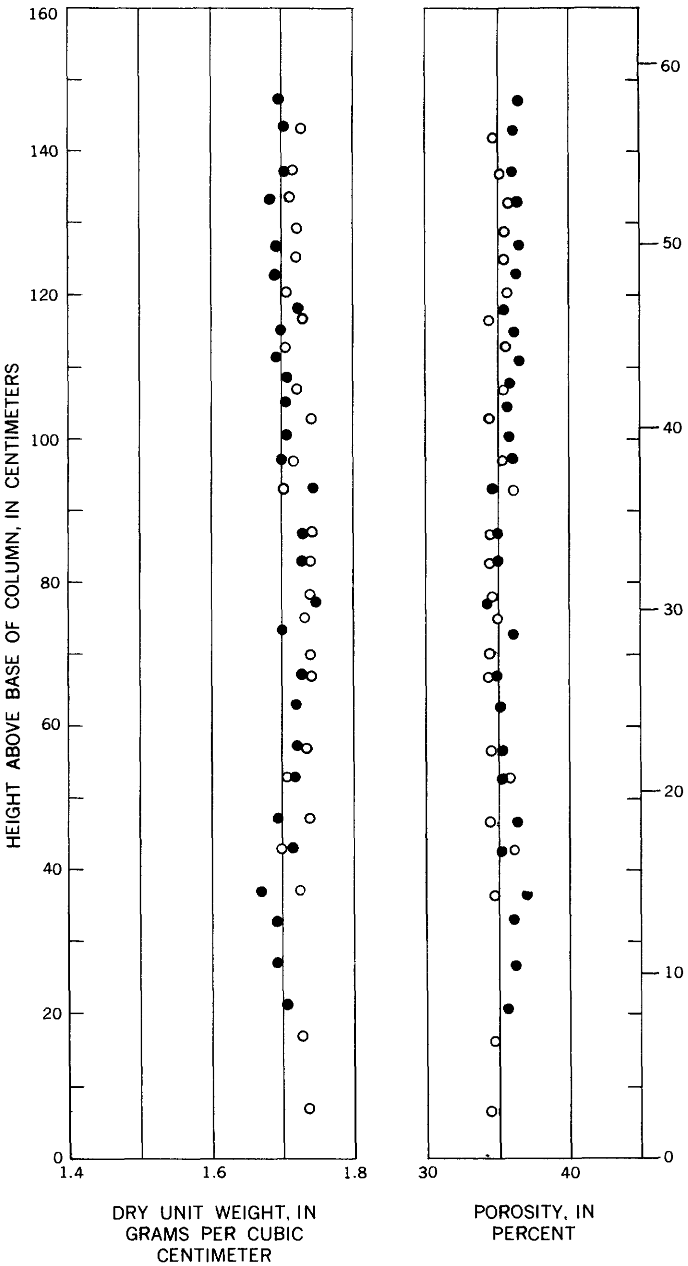

FIGURE 21.—Graph showing distribution of dry unit weight and porosity after draining columns of 20-mesh Del Monte sand. Solid circles refer to column 1; open circles refer to column 2.

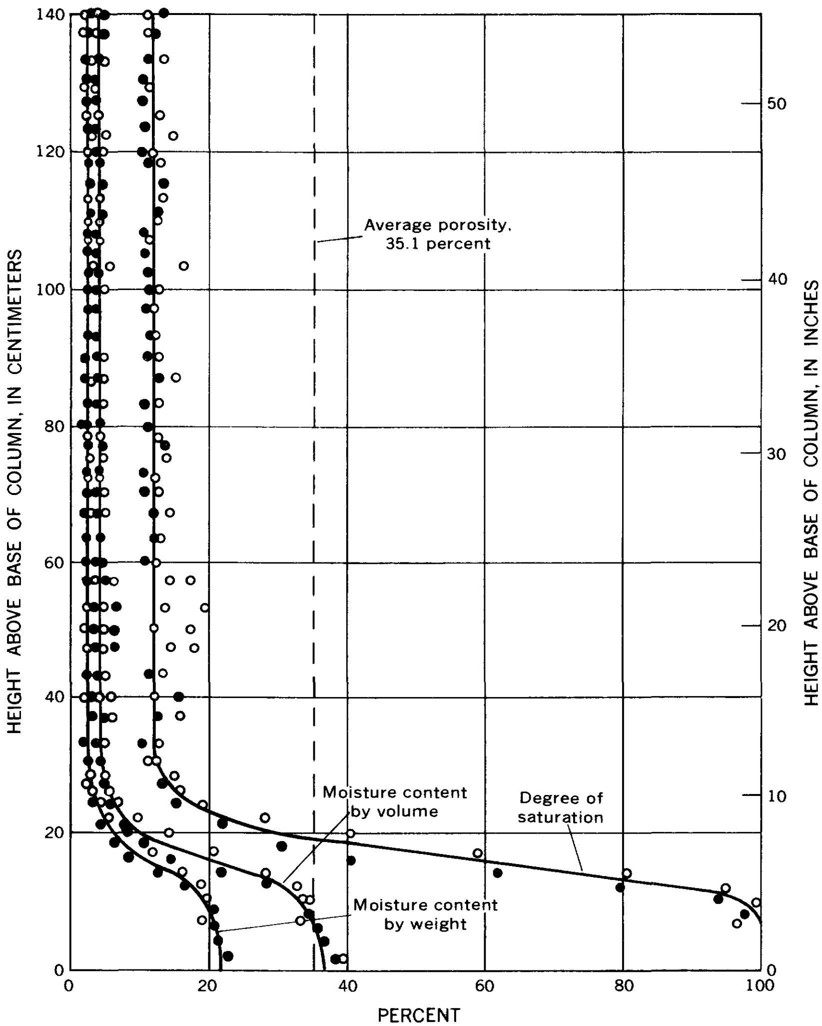

Figure 22.—Graph showing moisture retained after drainage of 20-mesh Del Monte sand. Solid circles refer to column 1; open circles refer to column 2.

more pronounced than for the Fresno medium sand. At heights greater than 30 cm, moisture content remained at 4 percent of volume.

The curve relating moisture content to tension is shown in figure 23. The hydraulic gradient at the completion of drainage was nearly zero in the section of the media below 30 cm for tests 1 and 2. Because the tension values in that section were very close to the heights of the tensiometers above the base of column, all the moisture values in the section were used in developing the curve. Above 30 cm in height the

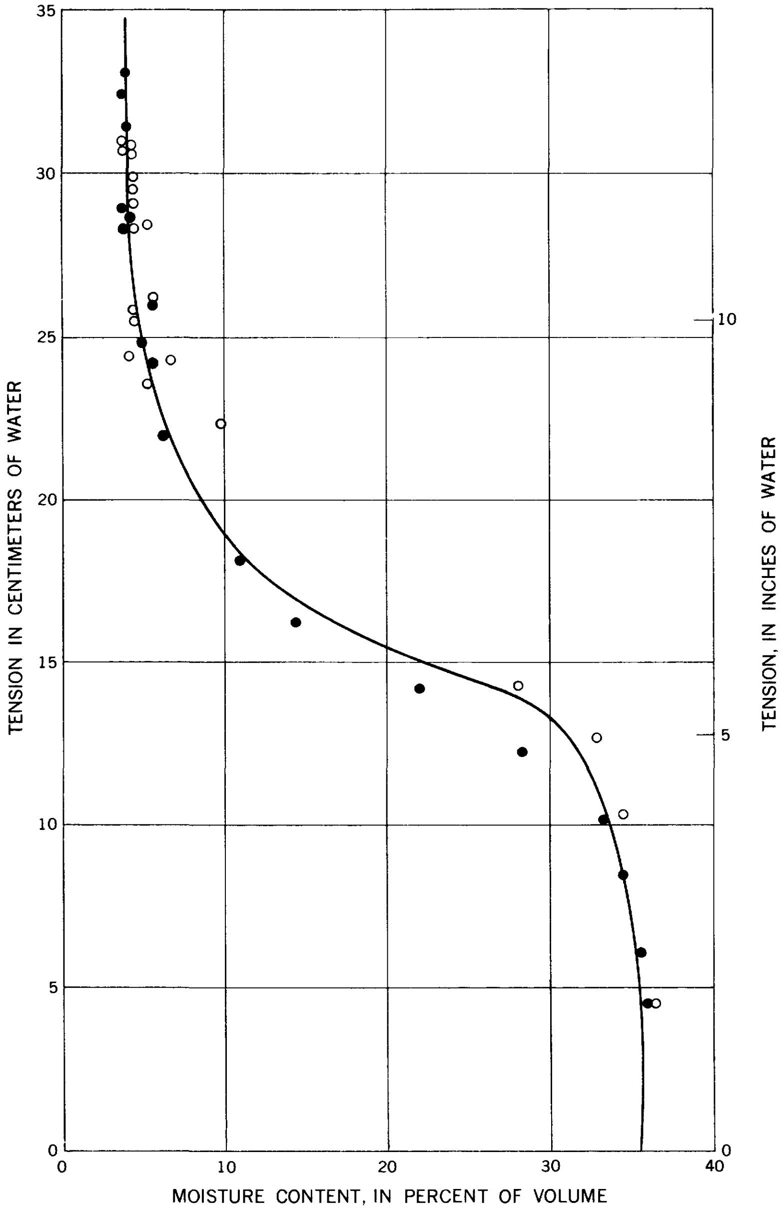

FIGURE 23.—Graph showing relation of moisture content to tension for 20-mesh Del Monte sand. Solid circles refer to column 1; open circles refer to column 2.

moisture and tension values of the sand in the segments containing tensiometers also were used in developing the curve (fig. 23).

As observed with the Fresno medium sand, the points from which the 20-mesh Del Monte sand moisture-tension curve was extrapolated are more scattered than the points representing the moisture-tension values for the 0.120-mm glass beads. The scatter is probably due to the greater heterogeneity, and consequently greater variation in porosity, of the Del Monte sand.

MOISTURE DISTRIBUTION AND DISCHARGE IN RELATION TO TIME OF DRAINAGE

Using the moisture-tension curve (fig. 23), the tension data (figs. 19 and 20) were converted to moisture content and are shown in figure 24 for test 1 and in figure 25 for test 2. The accumulated discharge compared with time of drainage for the two runs is shown in figure 26. After 1 hour of drainage, approximately 90 percent of the total discharge from the 2 columns had occurred. After 6 hours, over 97 percent, and after 12 hours, over 99 percent of the total discharge had occurred. The differences in discharge of the two columns are due to the different vertical thickness and a difference in outflow from the manometer system.

Although there was a noticeable change in tension between 12 and 24 hours, there was only a very small change in outflow or moisture content in the media as indicated by the outflow data and the moisture-distribution curves. (See figs. 24, 25, and 26.) Thus, although the tensions in the upper part of the column had not reached theoretical equilibrium conditions, it appears that all but a small amount of the potential drainage had occurred in 28 hours.

DRAINAGE OF LAYERED 20-MESH DEL MONTE SAND AND FRESNO MEDIUM SAND

The layered column consisted of a layer of 20-mesh Del Monte sand in the lower 49.5 cm of the column, overlain by a layer of Fresno medium sand extending to a height of 131.2 cm, and a layer of 20-mesh Del Monte sand extending from 131.2 to 170 cm.

TENSION IN RELATION TO TIME OF DRAINAGE

The vertical distribution of tension in the layered column during a 99-hour period of drainage is shown in figure 27.

Visual observation of the zone of apparent saturation during drainage indicated that the 20-mesh Del Monte sand in the lower section of the column was saturated until about half an hour after drainage started. The outflow data substantiated this observation by showing a sharp increase in outflow after about half an hour of drainage, indicating that the lower layer of Del Monte sand had then started to drain. After half an hour of drainage there was some evidence of a slight lag between tensiometer readings and actual tensions for several of the tensiometers. Although the half-hour tension curve thus represents only an approximate tension distribution, it at least should reflect the general trend of tension distribution during the early period of drainage.

The tension pattern during the early half-hour period indicates a very low hydraulic gradient in the bottom layer of Del Monte sand, a hydraulic gradient in excess of 1 in the middle layer of Fresno sand, and a hydraulic gradient close to 1 in the top layer of Del Monte sand. The saturated permeability of Fresno medium sand is 0.5 cc per sec per sq cm (cubic centimeter per second per square centimeter), and the saturated permeability of the 20-mesh Del Monte sand is 8 cc per sec per sq cm. Because the permeability of the Del Monte sand is about 16 times that of the Fresno sand, only a low hydraulic gradient would be necessary to cause water movement through the Del Monte sand from the overlying Fresno sand during the first half hour of drainage.

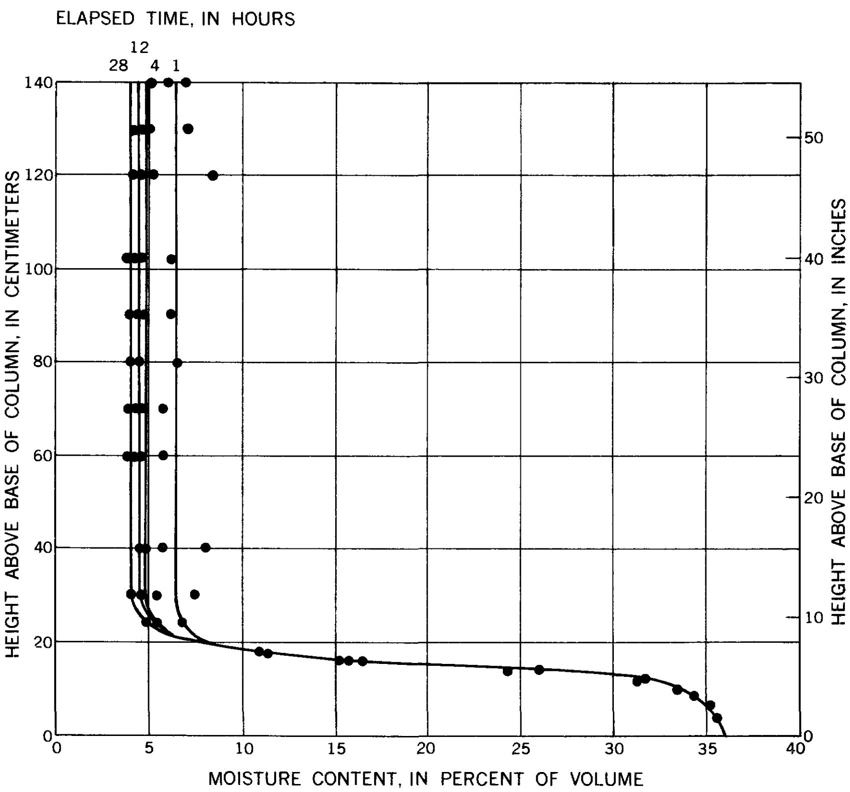

FIGURE 24.—Graph showing moisture distribution during drainage of 20-mesh Del Monte sand (column 1).

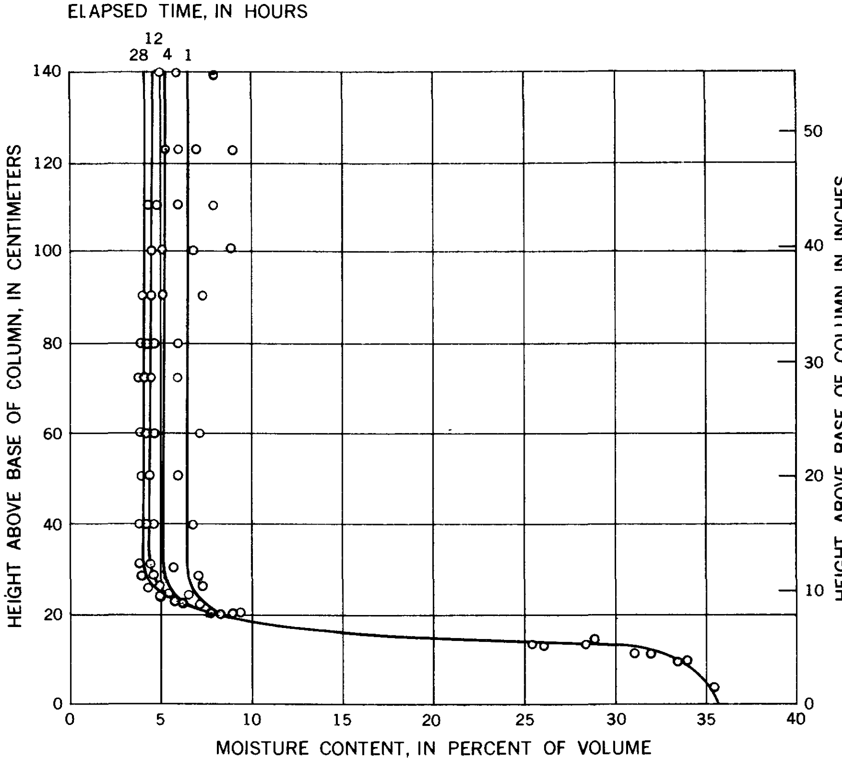

FIGURE 25.—Graph showing moisture distribution during drainage of 20-mesh Del Monte sand (column 2).

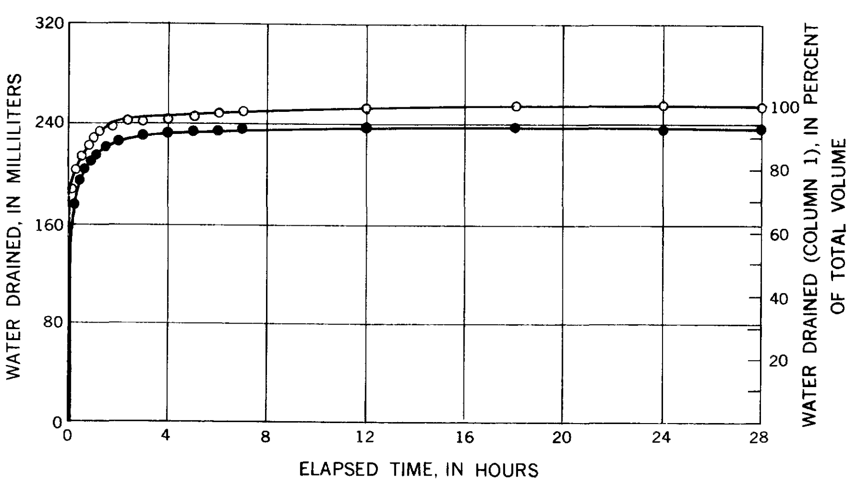

FIGURE 26.—Graph showing quantity of water drained from columns of 20-mesh Del Monte sand as related to time of drainage. Solid circles refer to column 1 (151.7 cm long); open circles refer to column 2 (147.5 cm long).

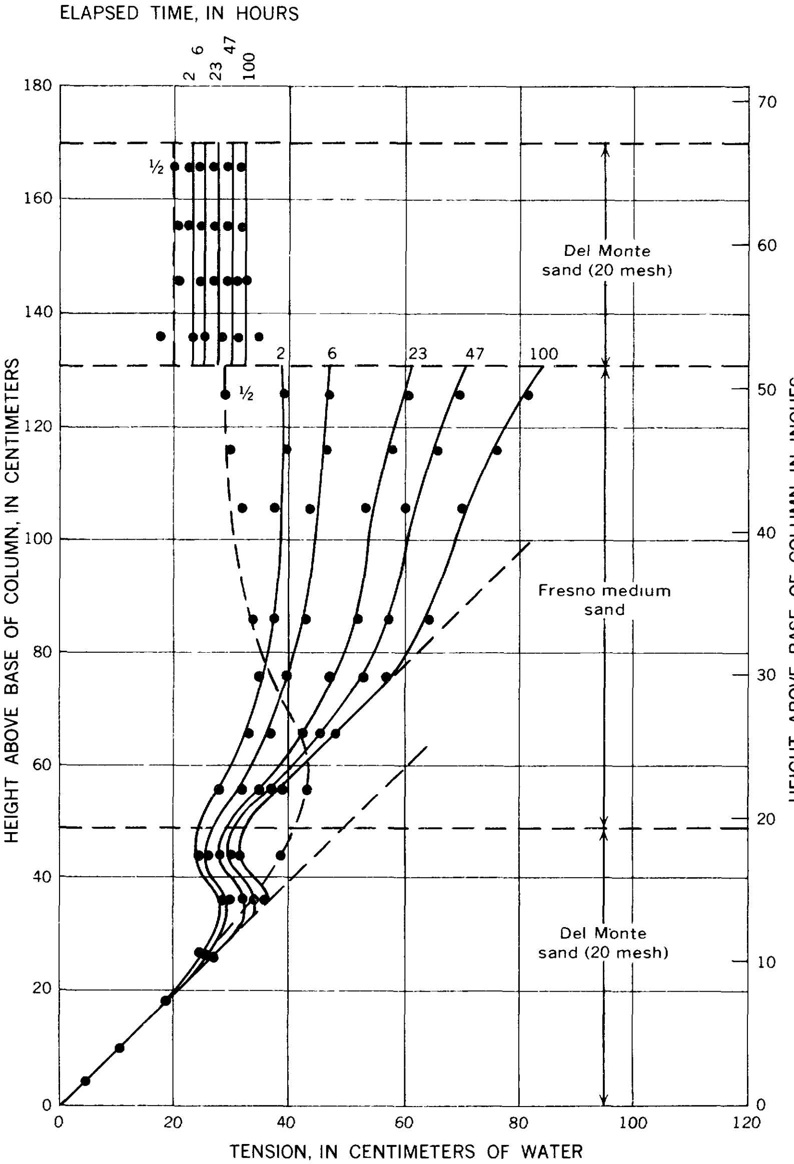

FIGURE 27.—Graph showing tension distribution during drainage of a layered column of 20-mesh Del Monte sand and Fresno medium sand.

Thus, in effect, the Del Monte sand was acting as a hanging water column during this period of drainage.

Two lines having a 1-to-1 slope are drawn in figure 27. The line starting at zero distance above the base of the column is the theoretical tension curve representing equilibrium drainage conditions for the Del Monte sand. The other line, in the layer of Fresno medium sand, is extrapolated from that part of the 99-hour tension curve that has a hydraulic gradient close to zero. This line crosses the left vertical axis at 19 cm. The tension at the top of the bottom layer of Del Monte sand or at the bottom of the layer of Fresno sand (49.5 cm above the base of the column) at the end of drainage was about 30.5 cm (the tension recorded at a height of 44 cm above the base of the column after 99 hours of drainage). In drainage of homogeneous columns of Fresno sand, the tension at 49.5 cm after drainage was approximately 49.5 cm. Thus, there was at this height an estimated difference of tension of 19 cm of water between the layered column and a homogeneous column of Fresno medium sand. It is assumed then that the pattern of tension distribution after about 100 hours of drainage within the Fresno sand in the layered column would be similar to that in a column of Fresno sand having a vertical thickness of about 112 cm. However, some adjustment would be necessary because of the changing tension in the underlying strata and because of water entering the media from the overlying strata. The lower boundary of the Fresno medium sand in the layered column then should be comparable in position to a height of 30.5 cm in a homogeneous column. A comparison of the tension curves for the Fresno medium sand in the layered column (fig. 27) with the curves for homogeneous columns of this same sand (figs. 11 and 12) supports this assumption.

After 2 hours of drainage the hydraulic gradient in the bottom layer of Del Monte sand was nearly zero in the section of the column between 0 and 25 cm and about 1 between 25 and 49.5 cm. After 100 hours, it was approximately zero from 0 and 35 cm and almost 1 from 35 to 49.5 cm. A similar pattern of hydraulic gradients at these heights was observed in the two drainage tests for the homogeneous columns of 20-mesh Del Monte sand (figs. 19 and 20).

The hydraulic gradient in the top layer of Del Monte sand (between 131.2 and 170 cm) was about one throughout the test. The hydraulic gradient and the tension values are similar to the values at comparable heights in the two drainage tests for homogeneous columns of 20-mesh Del Monte sand.

PHYSICAL AND HYDROLOGIC PROPERTIES AFTER DRAINAGE

Figures 28 and 29 show the vertical distribution of dry unit weight, porosity, moisture content and degree of saturation after drainage. As shown in figure 28, dry unit weights and porosities for the Del Monte sand do not vary appreciably whether in the top or bottom layer of the column. The average porosity of 35.1 percent and average dry unit weight of 1.72 g per cc for this sand in the layered column are similar to those values obtained for columns filled only with Del Monte sand (fig. 21).

Porosity and dry unit weight were consistent throughout the layer of Fresno medium sand. The average porosity was 37.0 percent and the average dry unit weight was 1.70 g per cc. These average values for the Fresno medium sand in the layered column are similar to those obtained for columns filled only with Fresno sand (fig. 13).

In figure 29 the moisture content and degree of saturation of the Del Monte sand in the layered column are shown to be similar to those values obtained in the drainage of columns filled only with 20-mesh Del Monte sand (fig. 22).

Considering that the bottom of the layer of Fresno sand in the layered column corresponds to a height of 49.5 cm in a homogeneous column, the moisture content and degree of saturation of the Fresno sand (fig. 29) correspond closely, especially in the upper part of the layer, to that obtained in the drainage of columns filled only with Fresno sand (fig. 14).

MOISTURE DISTRIBUTION AND DISCHARGE IN RELATION TO TIME OF DRAINAGE

The tension data, except those for one-half hour, were converted to moisture content by using the moisture-tension curve for Del Monte sand (fig. 23) and for Fresno medium sand (fig. 15). These moisture content data for various periods of drainage are shown in figure 30. The quantity of discharge of water in relation to time of drainage is shown in figure 31.

Because the bottom layer of Del Monte sand was functioning somewhat as a hanging water column during the early period of drainage, the tensions in this sand and for some distance in the overlying Fresno sand would not be an accurate reflection of moisture content. Consequently, the tensions for one-half hour of drainage were not converted to moisture contents. For the Del Monte sand, the moisture distribution for various periods of drainage in a layered column (fig. 30) was quite similar to that obtained from the drainage of columns filled only with Del Monte sand (figs. 24 and 25). As discussed in the section on tension, the vertical scale in figure 30 should be adjusted so that it reads 30.5 cm at the bottom of the layer of Fresno sand. The moisture contents in this layer then are similar to those obtained in the drainage of homogeneous columns of Fresno medium sand.

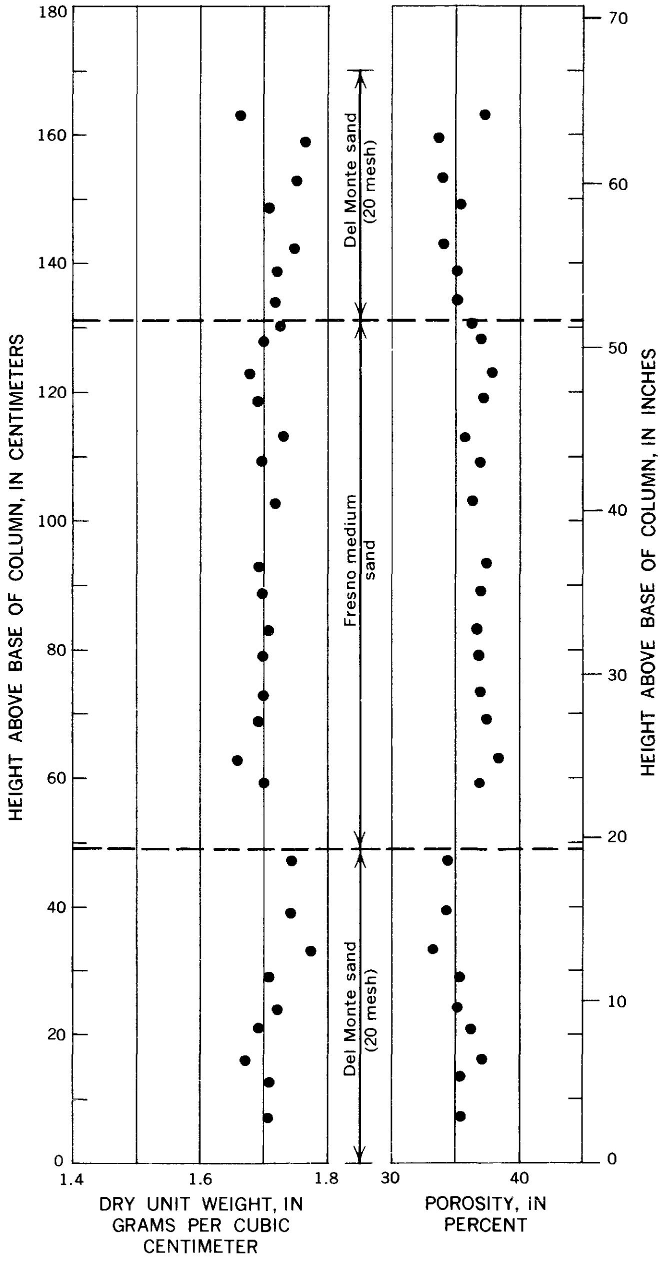

FIGURE 28.—Graph showing distribution of dry unit weight and porosity after draining a layered column of 20-mesh Del Monte sand and Fresno medium sand.

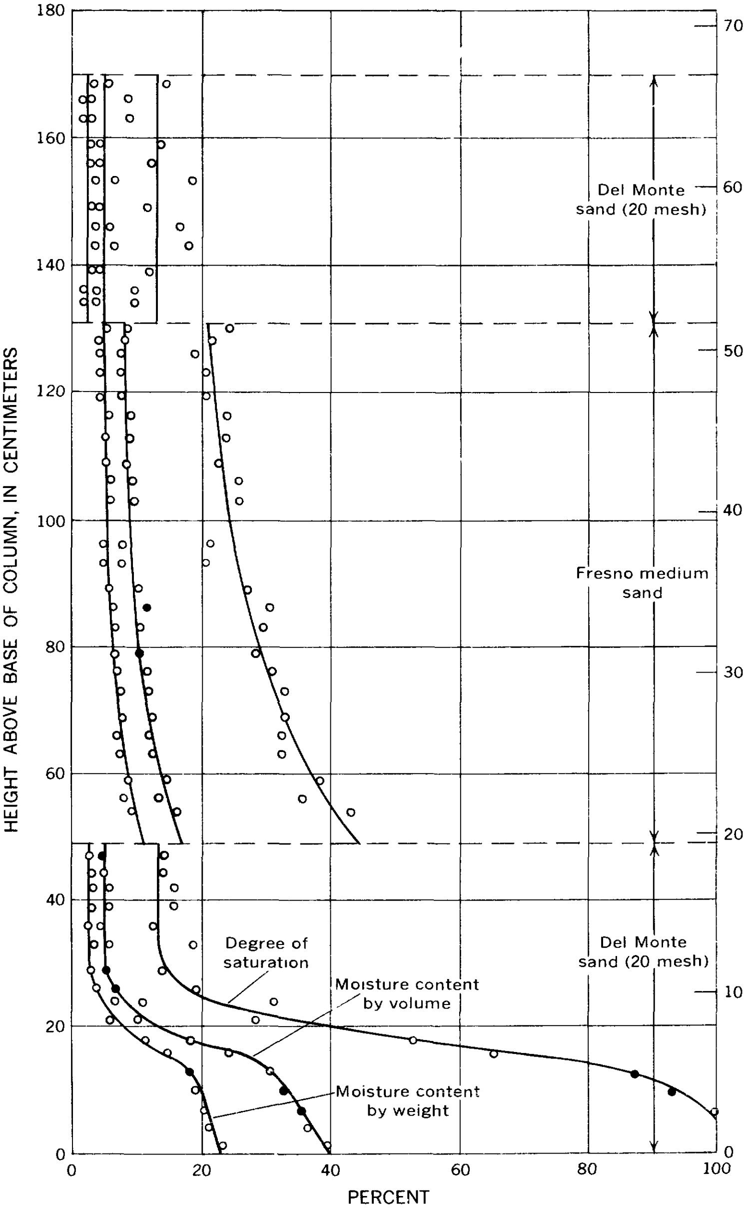

FIGURE 29.—Graph showing moisture retained after drainage of a layered column of 20-mesh Del Monte sand and Fresno medium sand.

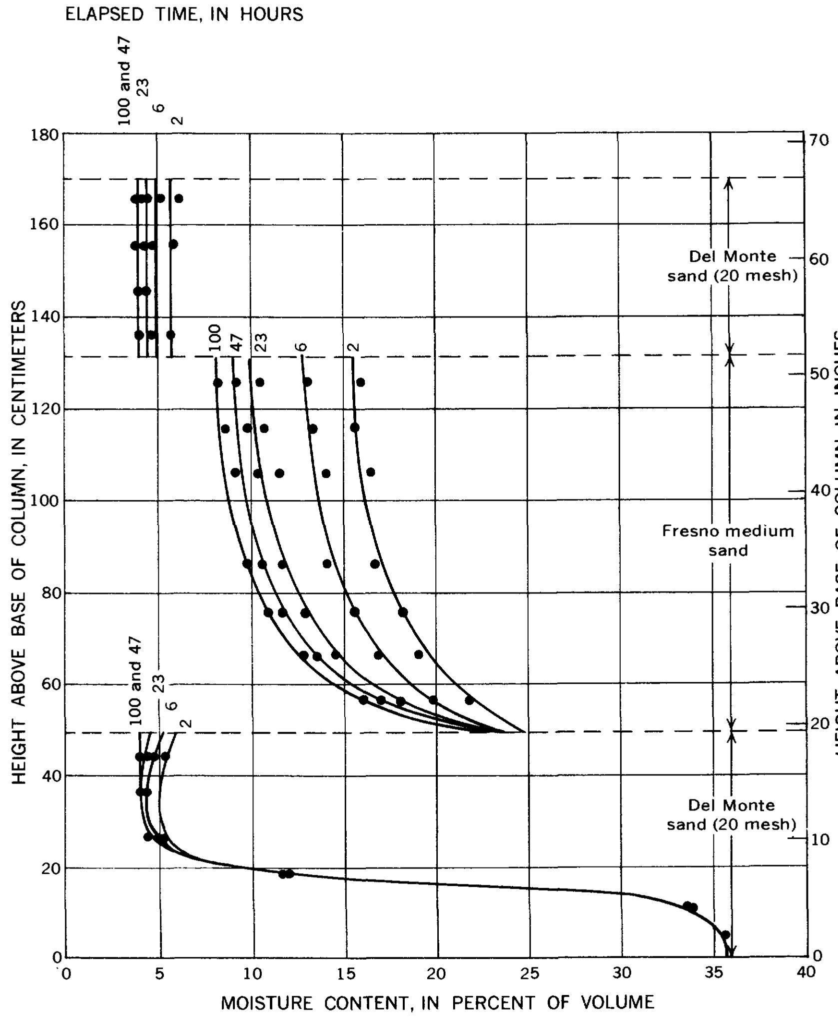

FIGURE 30.—Graph showing moisture distribution during drainage of a layered column of 20-mesh Del Monte sand and Fresno medium sand.

The outflow from the layered column (fig. 31) was greater, for equivalent time of drainage, than the outflow from a homogeneous column of Fresno sand (fig. 18). The outflow from the layered column was 72 ml after 20 minutes and 99 ml after 30 minutes of drainage. The outflow for column 1 of Fresno sand was 54 ml after 20 minutes and 70 ml after 30 minutes of drainage. This was probably due to the bottom layer of Del Monte sand acting as a hanging water column while at the same time the top layer of Del Monte sand was contributing a greater quantity of drainage than would be contributed by a similar layer of Fresno sand.

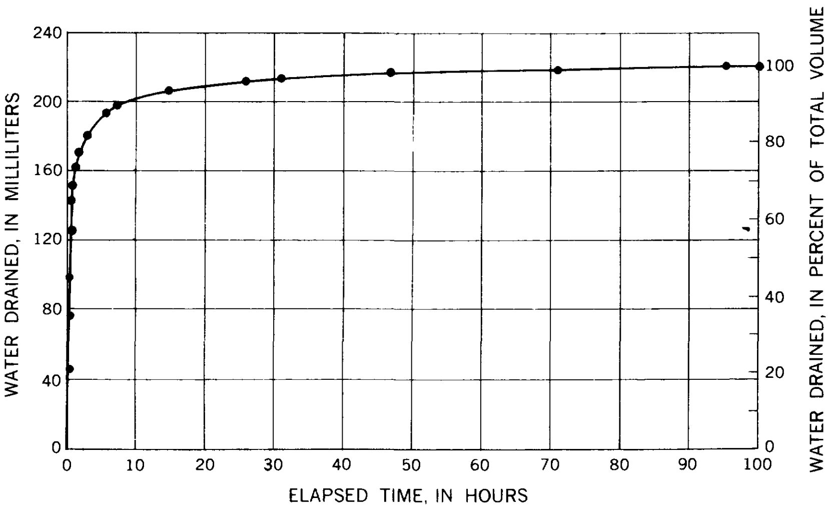

FIGURE 31.—Graph showing quantity of water drained from a layered column of 20-mesh Del Monte sand and Fresno medium sand.

SUMMARY

Three sand-size materials, 0.120-mm glass beads (very fine sand size), a sand collected near Fresno, Calif. (medium-sand size) and 20-mesh Del Monte sand (coarse-sand size) were packed in columns consisting of 2- and 4-cm lucite segments having an inside diameter of 2.8 cm. A column consisting of layers of 20-mesh Del Monte sand and Fresno medium sand was also packed. The thickness of the media in the columns ranged between 141 and 170 cm. The media was wetted from below and drained under controlled conditions of temperature and humidity while outflow measurements were recorded. Tensiometers were installed at selected locations and tension readings were recorded during drainage. After drainage the media contained in each lucite segment was sampled for determinations of dry unit weight, porosity, moisture content, and degree of saturation, and these values were compared. The tension values recorded during drainage of the media were converted to moisture content by use of a curve that related moisture content to tension.

Test results from the drainage of 20-mesh Del Monte sand indicated that this sand had a high permeability at low tensions—0 to approximately 12 cm of water—and that the permeability decreased very rapidly with increasing tension up to tensions of about 25 cm, at which time the flow rate was only a small fraction of the initial flow rate and all but a small fraction of the potential drainage had occurred.

Drainage data for the 0.120-mm glass beads and Fresno medium sand indicated a lower permeability at the lower tensions than did the coarser textured 20-mesh Del Monte sand, but the permeability did not decrease as rapidly with increasing tension.

The data indicate that moisture equilibrium in the Del Monte sand would require tensions of as much as 150 cm and periods of drainage much in excess of the period of this study. Furthermore, experimental techniques capable of developing this tension for such long periods, as much as 1 year, would require precision humidity and temperature controls beyond the capabilities of present installations in the Hydrologic Laboratory.

The hydraulic gradient in the lower sections of the columns remained close to zero throughout the drainage test. The thickness of this zone of low hydraulic gradient increased with time of drainage.

In the upper sections of the columns of all three materials the hydraulic gradient was close to one during the early periods of drainage. It remained close to one throughout the drainage test for 20-mesh Del Monte sand but decreased with time of drainage for the 0.120-mm glass beads and Fresno medium sand, reaching a hydraulic gradient close to seven-tenths for Fresno medium sand and for the 0.120-mm glass beads at the end of the drainage tests.

The zone of capillary saturation was approximately 12 cm for the 20-mesh Del Monte sand, 53 cm for the 0.120-mm glass beads, and 12 cm for the Fresno medium sand. Measurements of the degree of saturation of these zones after drainage indicated that they were more than 90 percent saturated.

The moisture-distribution curve for the homogeneous 0.120-mm glass beads showed a much thicker zone of capillary saturation and a thinner and more sharply defined funicular zone than did the moisture-distribution curve for the heterogeneous Fresno medium sand.

A plot of moisture content and tension for the three materials indicated a much narrower range of scatter for data on the drainage of 0.120-mm glass beads than on the Fresno medium and 20-mesh Del Monte sand. This is probably caused by the more homogeneous nature of the glass beads.

Adjacent values of porosity and dry unit weight were comparable throughout the columns for the 0.120-mm glass beads and the 20-mesh Del Monte sand. For columns of Fresno medium sand, however, adjacent values of the porosity and dry unit weight were similar in the middle and upper sections by dissimilar in the lower section of the column.

The moisture-distribution data and the outflow data indicated the time when drainage occurred, as well as the location within the column where this discharge occurred. Most of the outflow from these sand-size materials occurred in the earlier hours of drainage.

After 1 hour of drainage, approximately 90 percent of the total measured discharge had occurred in the 20-mesh Del Monte sand, 60 percent in the 0.120-mm glass beads, and 50 percent in the Fresno sand. After 5 hours 90 percent of the total measured discharge had occurred in the 0.120-mm glass beads, and after 25 hours 90 percent had occurred in the Fresno sand.

In drainage of a layered column consisting of a bottom layer of 20-mesh Del Monte sand, a middle layer of Fresno medium sand, and a top layer of 20-mesh Del Monte sand, the bottom layer functioned as a hanging water column, accelerating the drainage of the overlying media until the visual zone of saturation had passed through the layer of Fresno sand. After the bottom layer started to drain, the pattern of tension and moisture distribution in the bottom and top layers showed similar trends to that observed in homogeneous columns of Del Monte sand.

The pattern of tension and moisture distribution in the middle layer of Fresno medium sand after drainage was similar to that in a homogeneous column of this sand.

In the laboratory this study demonstrates the phenomena of slow drainage of porous materials—even where those materials may be as coarse as sands. Meinzer (1923) and Wenzel (1942) both cautioned that the maximum specific yield is reached only after a drainage period of considerable length. The drainage period to reach maximum specific yield may range from a few hours for coarse-textured materials to months for the fine-textured materials.

The effect of slow drainage on the specific yield of porous materials is emphasized by the experimental data in this report. These data indicate that 90 percent of the maximum specific yield was reached in 1 hour for 20-mesh Del Monte sand (uniform, coarse sand), in 5 hours for 0.120-mm glass beads (very uniform, very fine to fine sand), and in 25 hours for Fresno sand (less uniform, medium sand).

Although most of the drainage, or the largest percentage of the specific yield, was reached in this study during the early hours of drainage, a very long time would have been required to reach drainage equilibrium. Even for the sand-size materials used in this study, the authors estimate that from 2 months to more than one year would be required to reach drainage equilibrium, and thus give the maximum specific yield. Equipment for control of humidity and temperature was not sufficiently refined to permit drainage of samples for longer periods without the effects of evaporation being too great. However, sufficient drainage probably had taken place for all practical purposes.

Such slow drainage, especially if even finer textured materials were present, naturally would have a great effect upon the specific yield obtained by short-term pumping tests in the field. Under most field conditions, the maximum specific yield may not be obtained until after many days of pumping.

REFERENCES

Buckingham, Edgar, 1907, Studies on the movement of soil moisture: U.S. Dept. Agriculture Bull. 38, p. 29–61.

Coleman, E. A., 1946, A laboratory study of lysimeter drainage under controlled soil-moisture tension: Soil Sci., v. 62, p. 365.

Day, P. R., and Luthin, J. N., 1956, A numerical solution of the differential equation of flow for a vertical drainage problem: Soil Sci. Soc. America Proc., v. 20, p. 443–447.

Eckis, Rollin, and Gross, P. L. K., 1934, South Coastal Basin investigation—geology and ground-water storage capacity of valley fill: California Div. Water Resources Bull. 45, 273 p.

Gatewood, J. S., and others, 1950, Use of water by bottom-land vegetation in lower Safford Valley, Arizona: U.S. Geol. Survey Water-Supply Paper 1103, p. 81–92.

Hazen, Allen, 1892, Experiments upon the purification of sewage and water at the Lawrence Experimental Station, No. 1, 1889 to Dec. 31, 1891: Massachusetts State Board Health Pub., no. 34, p. 425–633.

Johnson, A. I., Morris, D. A., and Prill, R. C., 1961, Specific yield and related properties—an annotated bibliography: Denver, Colo., Hydrologic Laboratory Bibliography No. 2, U.S. Geol. Survey open-file rept., 245 p.

Johnson, A. I., Prill, R. C., and Morris, D. A., 1963, Specific yield—column drainage and centrifuge moisture content: U.S. Geol. Survey Water-Supply Paper 1662–A, 60 p.

King, F. H., 1899, Principles and conditions of the movement of ground water: U.S. Geol. Survey 19th Ann. Rept., pt. 2, p. 85–91.

Lambe, T. W., 1951, Capillary phenomena in cohesionless soils: Am. Soc. Civil Engineers Trans., v. 116, p. 401–432.

Lebedeff, A. F., 1927, The movement of ground and soil waters: Internat. Cong. Soil Sci. Proc., v. 1, p. 459–494.

Leverett, M. G., 1941, Capillary behavior in porous solids: Am. Inst. Mining Metall. Engineers Trans., v. 1942, p. 152–168.

Luthin, J. N., and Miller, R. D., 1953, Pressure distribution in soil columns draining into the atmosphere: Soil Sci., Soc. America Proc., v. 17, p. 329–333.

Marx, J. W., 1956, Determining gravity-drainage characteristics on the centrifuge: Jour. Petroleum Technology, v. 8, p. 88–91.

Meinzer, O. E., 1923, Outline of ground-water hydrology: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Morris, D. A., and Kulp, W. K., 1961, Mechanical uniform packing of porous media : U.S. Geol. Survey Prof. Paper 424–D, p. D31–D32.

Piper, A. M., and others, 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geol. Survey Water-Supply 780, p. 101–122.

Prill, R. C., 1961, Comparison of drainage data obtained by the centrifuge and column drainage methods, *in* Geological Survey Research 1961: U.S. Geol. Survey Prof. Paper 424–D, Art. 434, p. D399–D401.

Prill, R. C., and Johnson, A. I., 1959, Effect of temperature on moisture contents as determined by centrifuge and tension techniques: Am. Soc. Testing Materials, Spec. Tech. Pub. 254, p. 340–349.

Richards, L. A., and Moore, D. C., 1952, Influence of capillary conductivity and depth of wetting on moisture retention in soil: Am. Geophys. Union Trans., v. 33, no. 4, p. 531–540.

Smith, W. O., 1933, The final distribution of retained liquid in an ideal uniform soil: Physics, v. 4, p. 425–438.

——— 1961, Mechanism of gravity drainage and its relation to specific yield of uniform sands: U.S. Geol. Survey Prof. Paper 402–A.

Stahl, R. F., Martin, W. A., and Huntington, R. L., 1943, Gravitational drainage from unconsolidated Wilcox sand: Am. Inst. Mining Metall. Engineers Trans., v. 151, p. 138–146.

Stearns, H. T., Robinson, T. W., and Taylor, G. H., 1930, Geology and water resources of the Mokelumne area, California: U.S. Geol. Survey Water-Supply Paper 619, p. 151–172.

Terwillinger, P. L., and others, 1951, An experimental and theoretical investigation of gravity drainage performance: Am. Inst. Mining Metall. Engineers Trans., v. 192, p. 285–296.

Versluys, Jan, 1917, Die Kapillarität der Boden: Inst. Mitt. J. Bodenk, v. 7, p. 117–140.

——— 1931, Can absence of edge-water encroachment in certain oil fields be ascribed to capillarity?: Am. Assoc. Petroleum geologists Bull., v. 15, pt. 1, p. 189–200.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U.S. Geol. Survey Water-Supply Paper 887.

White, W. N., 1932, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: U.S. Geol. Survey Water-Supply Paper 659–A, 106 p.