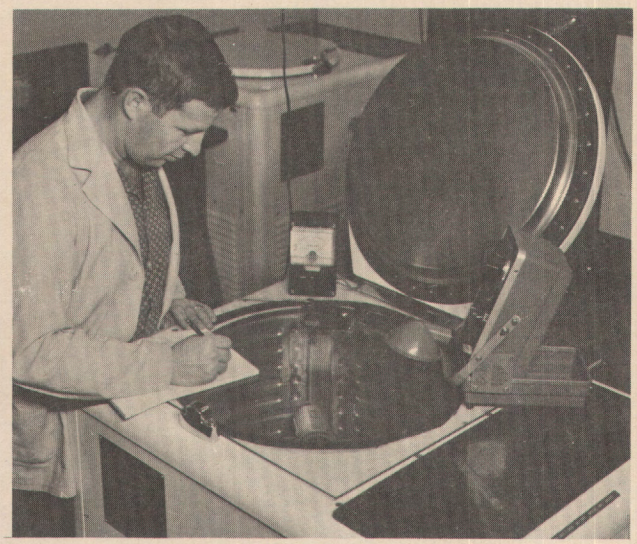
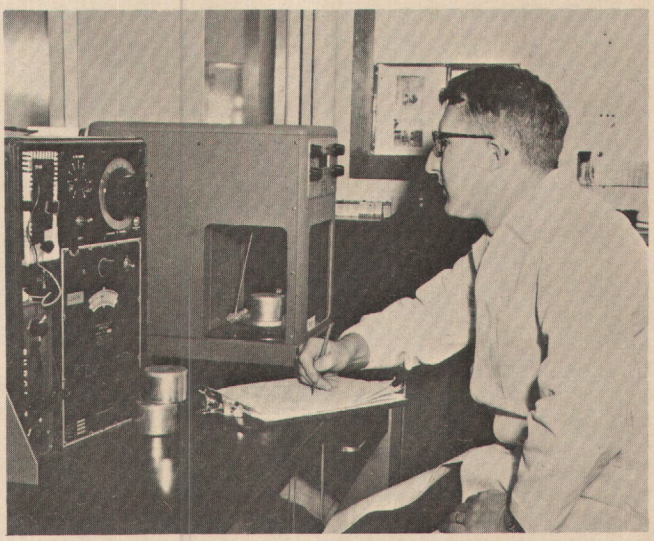


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SPECIFIC YIELD

LABORATORY EXPERIMENTS SHOWING THE EFFECT OF TIME ON COLUMN DRAINAGE

PREPARED IN COOPERATION
WITH THE CALIFORNIA
DEPARTMENT OF WATER
RESOURCES



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.

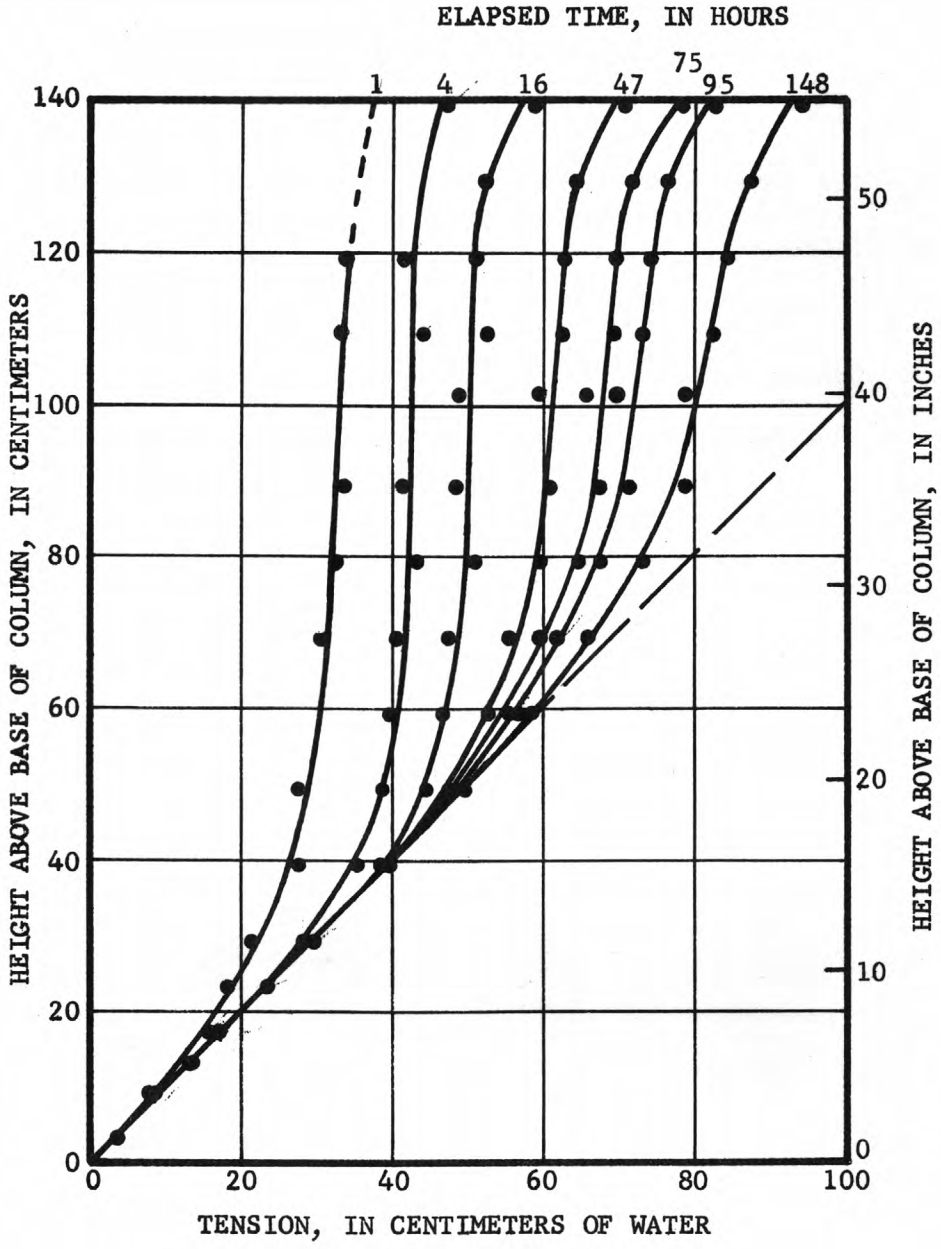


Figure 11.--Tension distribution during drainage of Fresno medium sand (column 1).

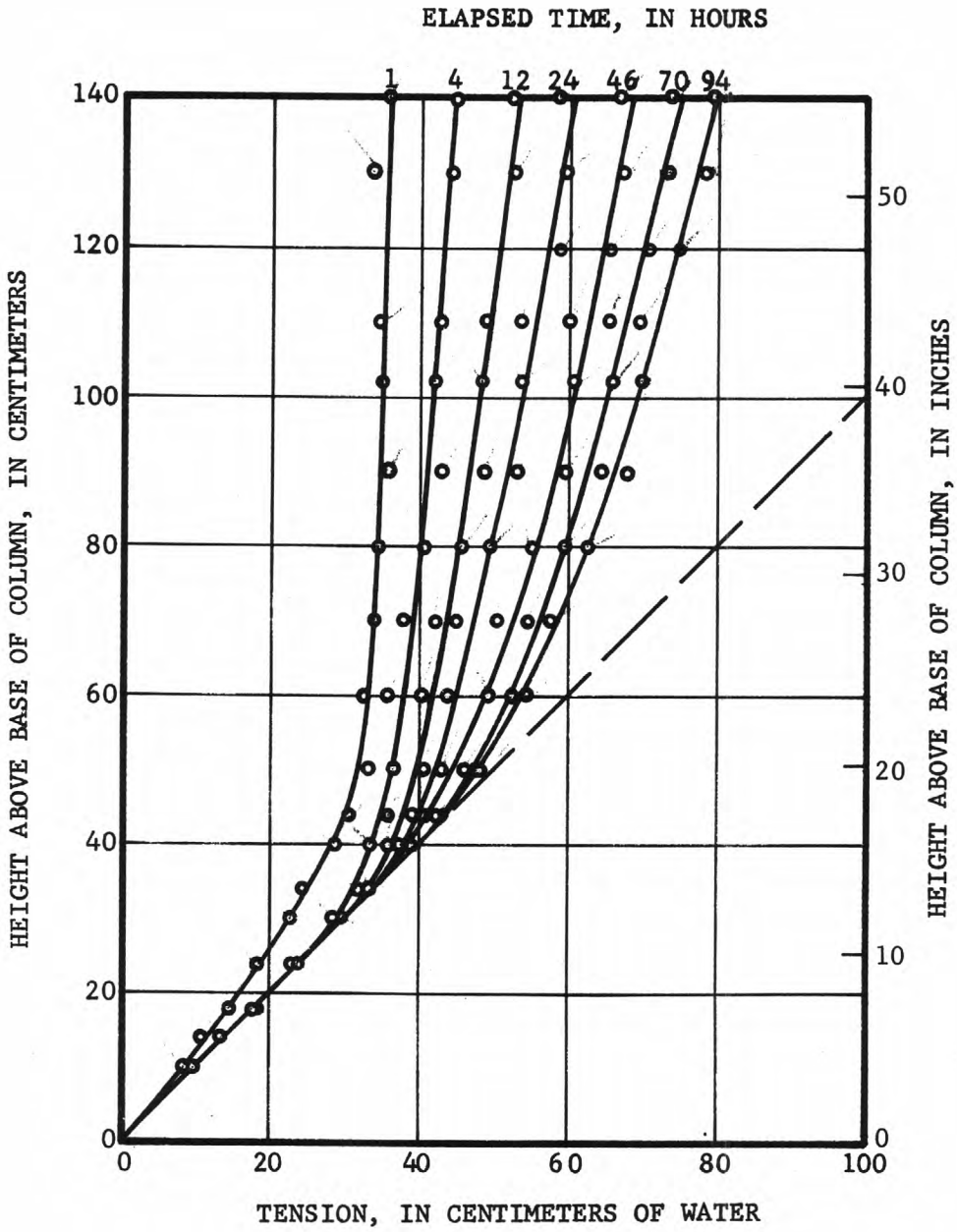


Figure 12.--Tension distribution during drainage of Fresno medium sand (column 2).

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

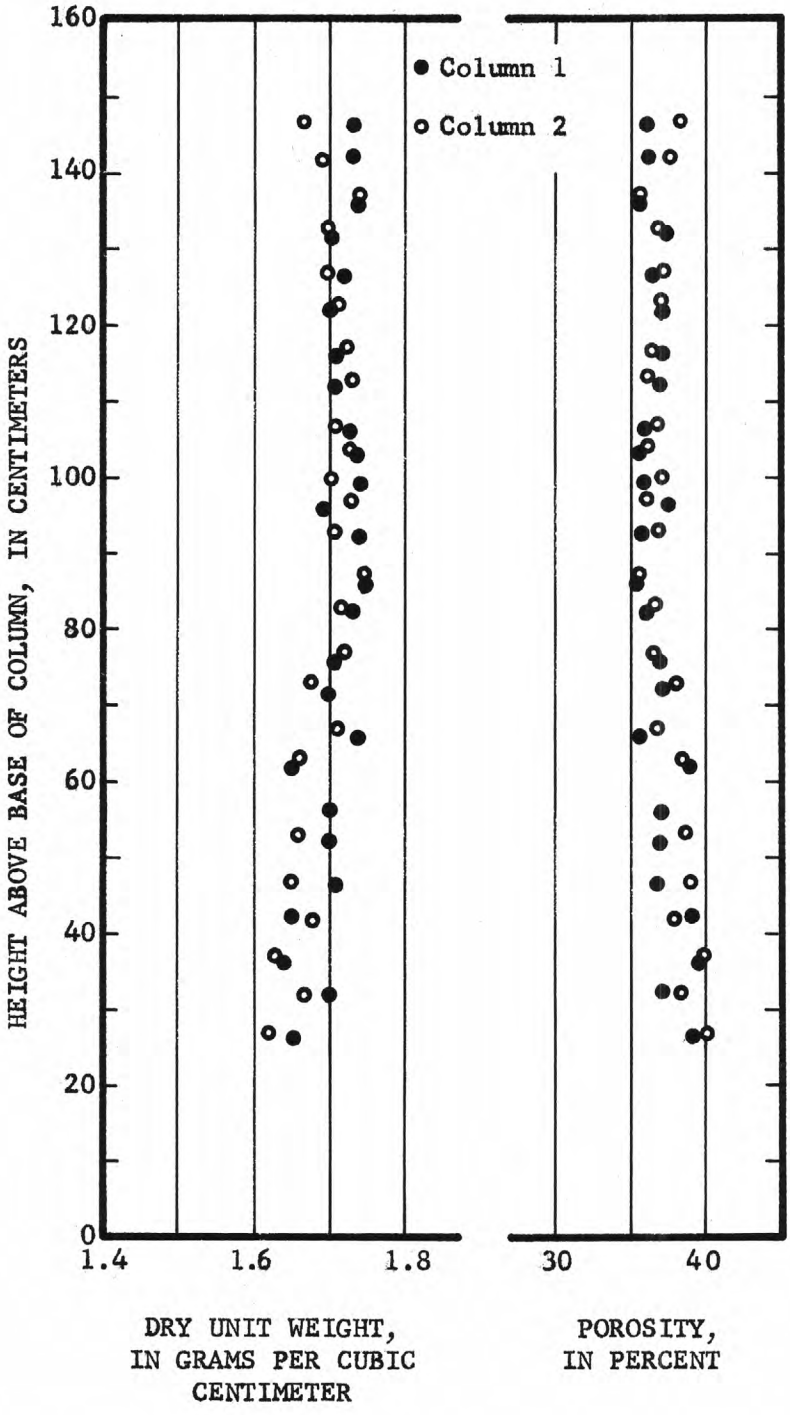


Figure 13.--Distribution of dry unit weight and porosity after draining columns of Fresno medium sand.

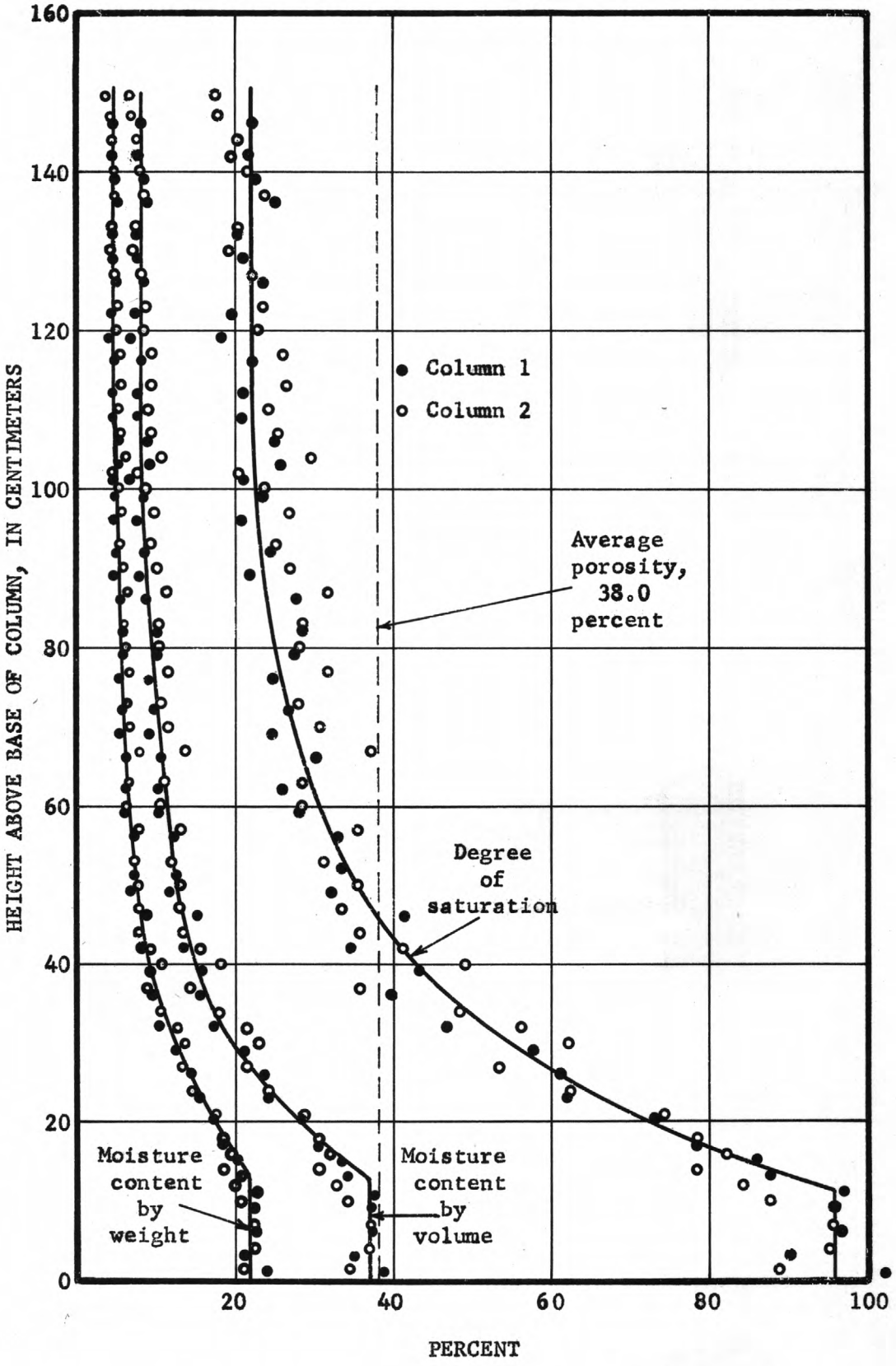


Figure 14.--Moisture retained after drainage of Fresno medium sand.

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.

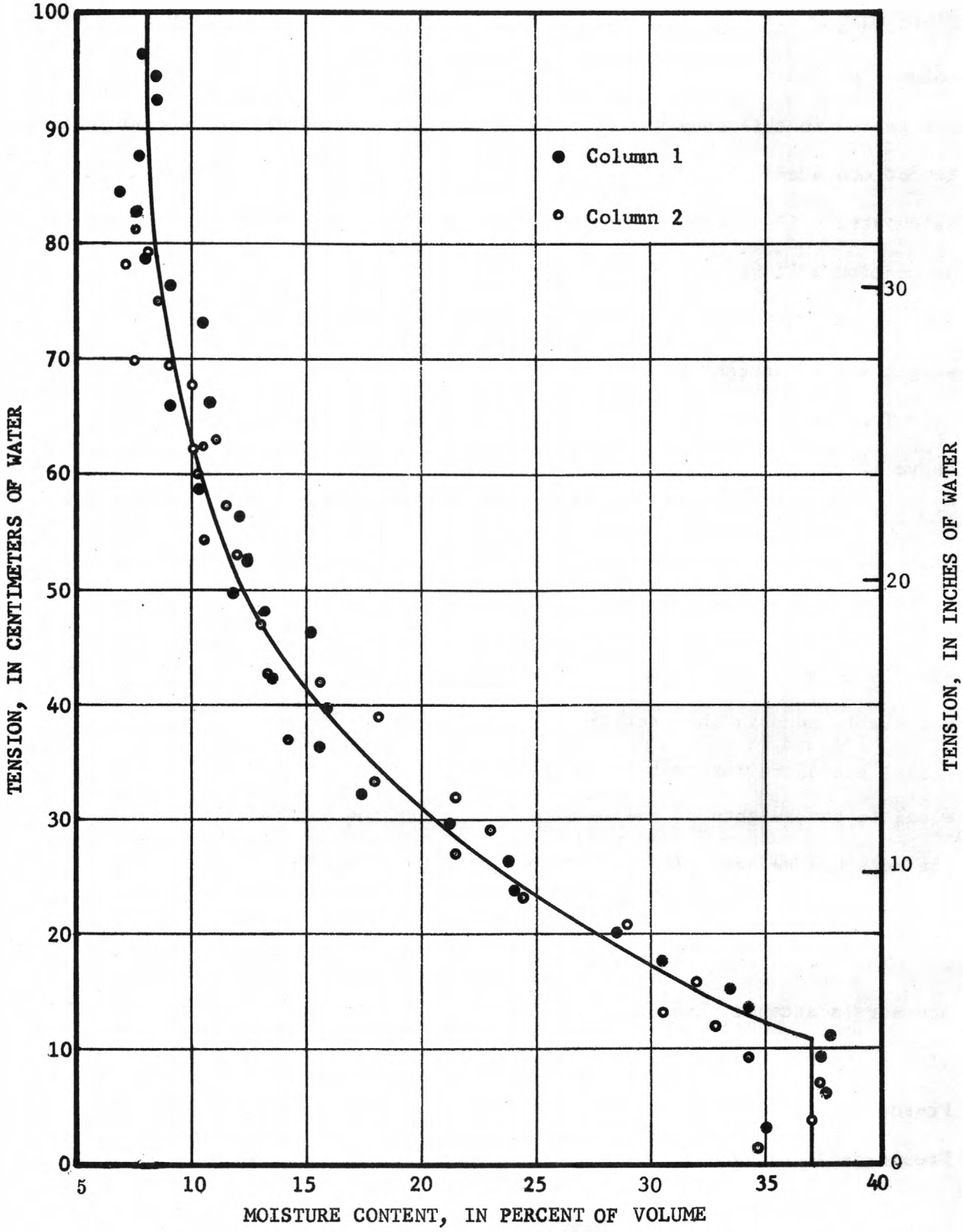


Figure 15.--Relation of moisture content to tension for Fresno medium sand.

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 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.

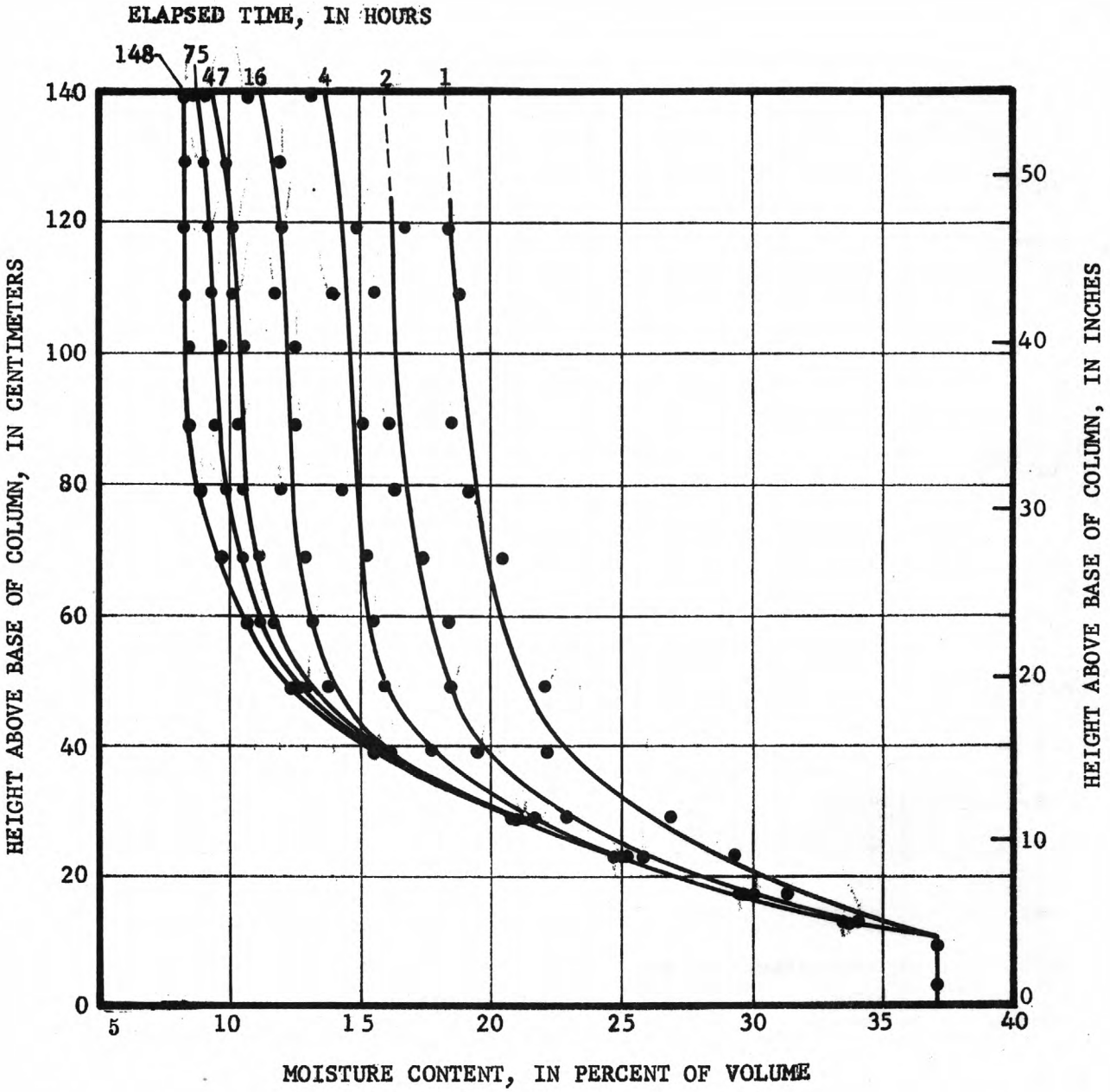


Figure 16.--Moisture distribution during drainage of Fresno medium sand (column 1).

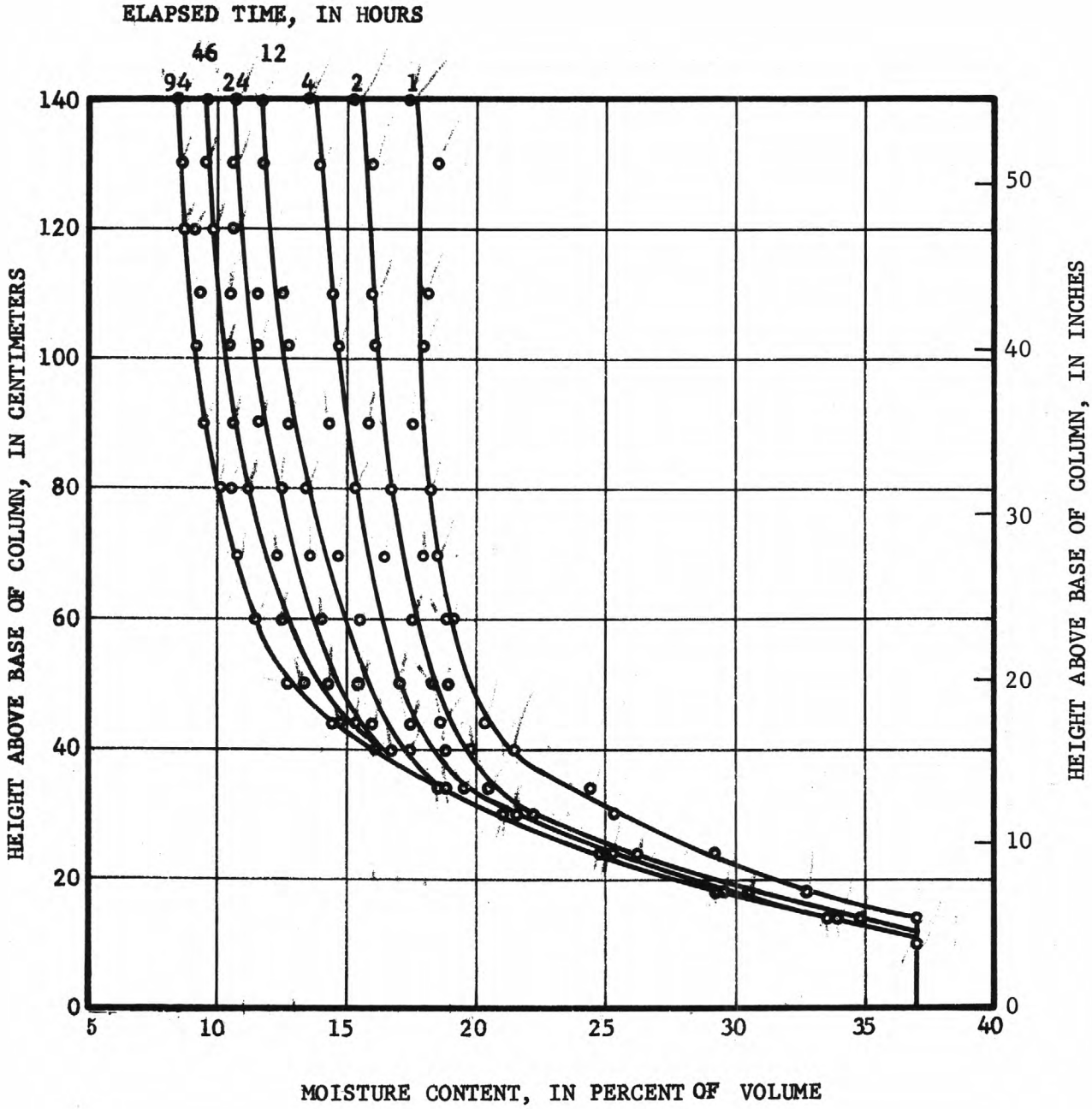


Figure 17.--Moisture distribution during drainage of Fresno medium sand (column 2).

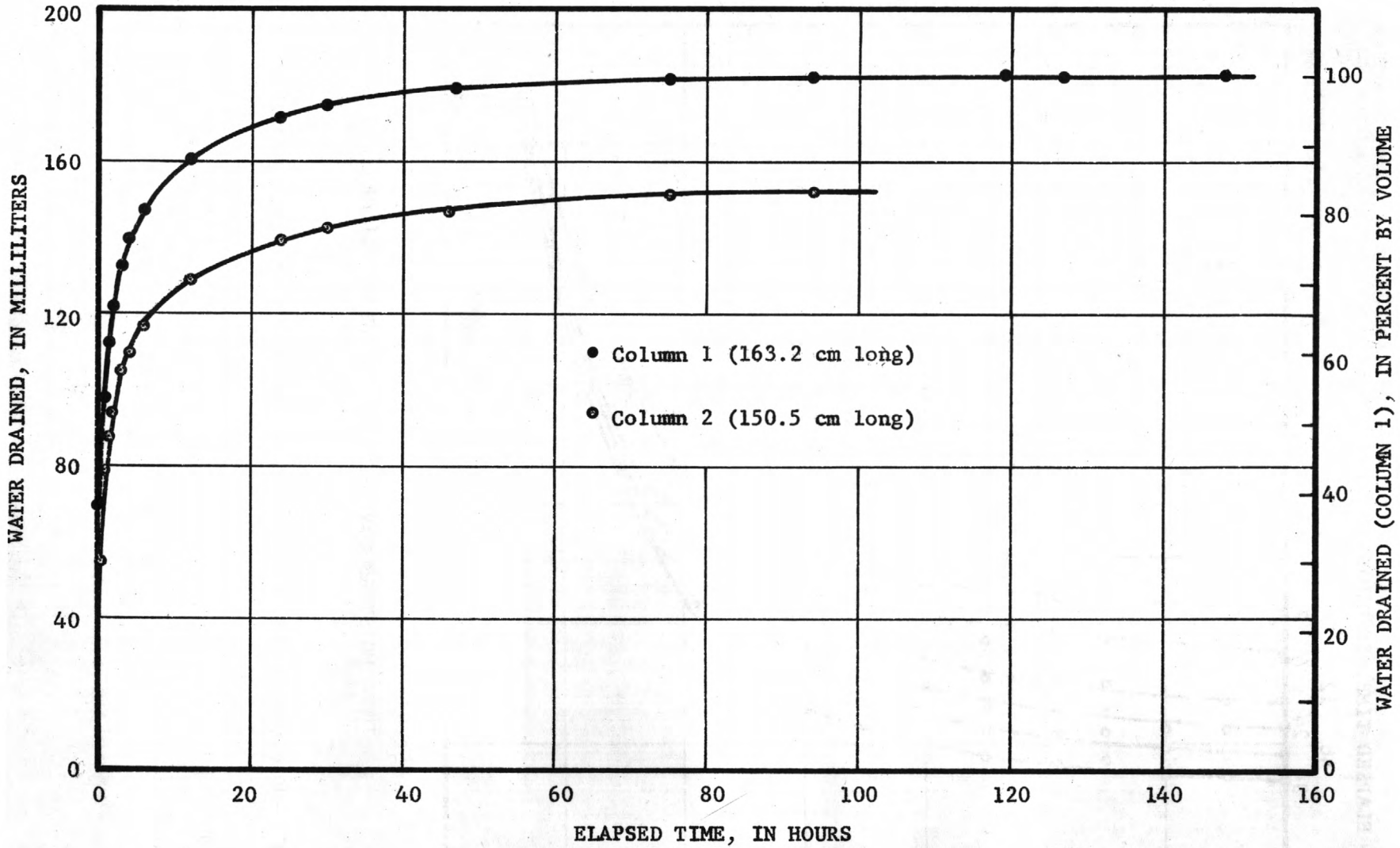


Figure 18.--Quantity of water drained from columns of Fresno medium sand as related to time of drainage.

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. 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.

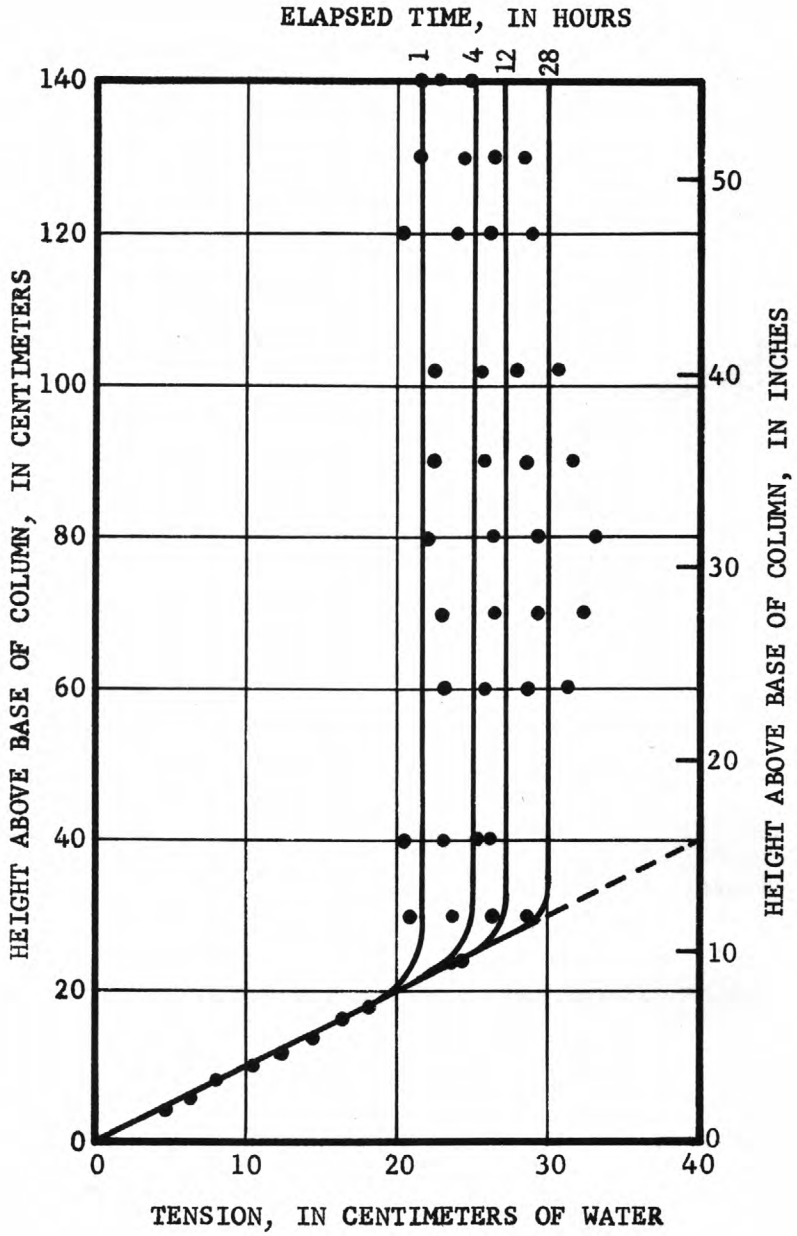


Figure 19.--Tension distribution during drainage of 20-mesh Del Monte sand (column 1).

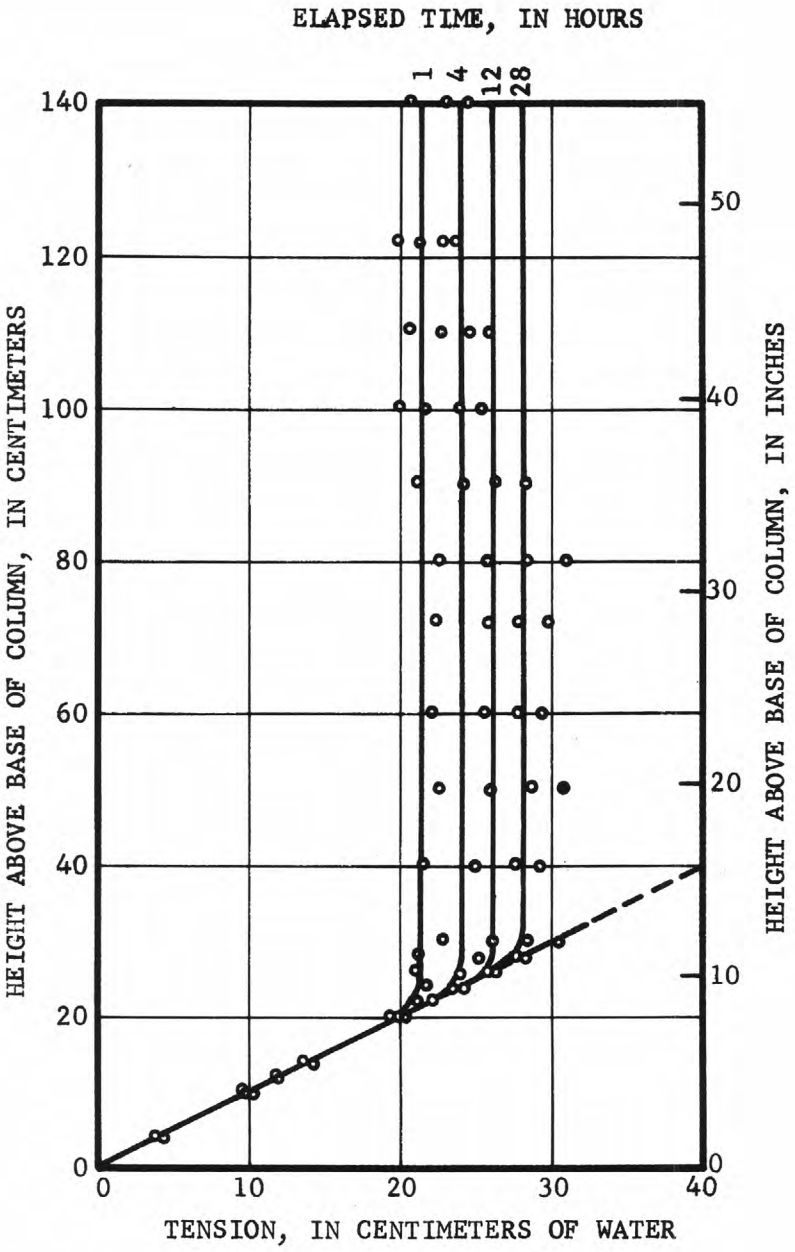


Figure 20.--Tension distribution during drainage of 20-mesh Del Monte sand (column 2).

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.

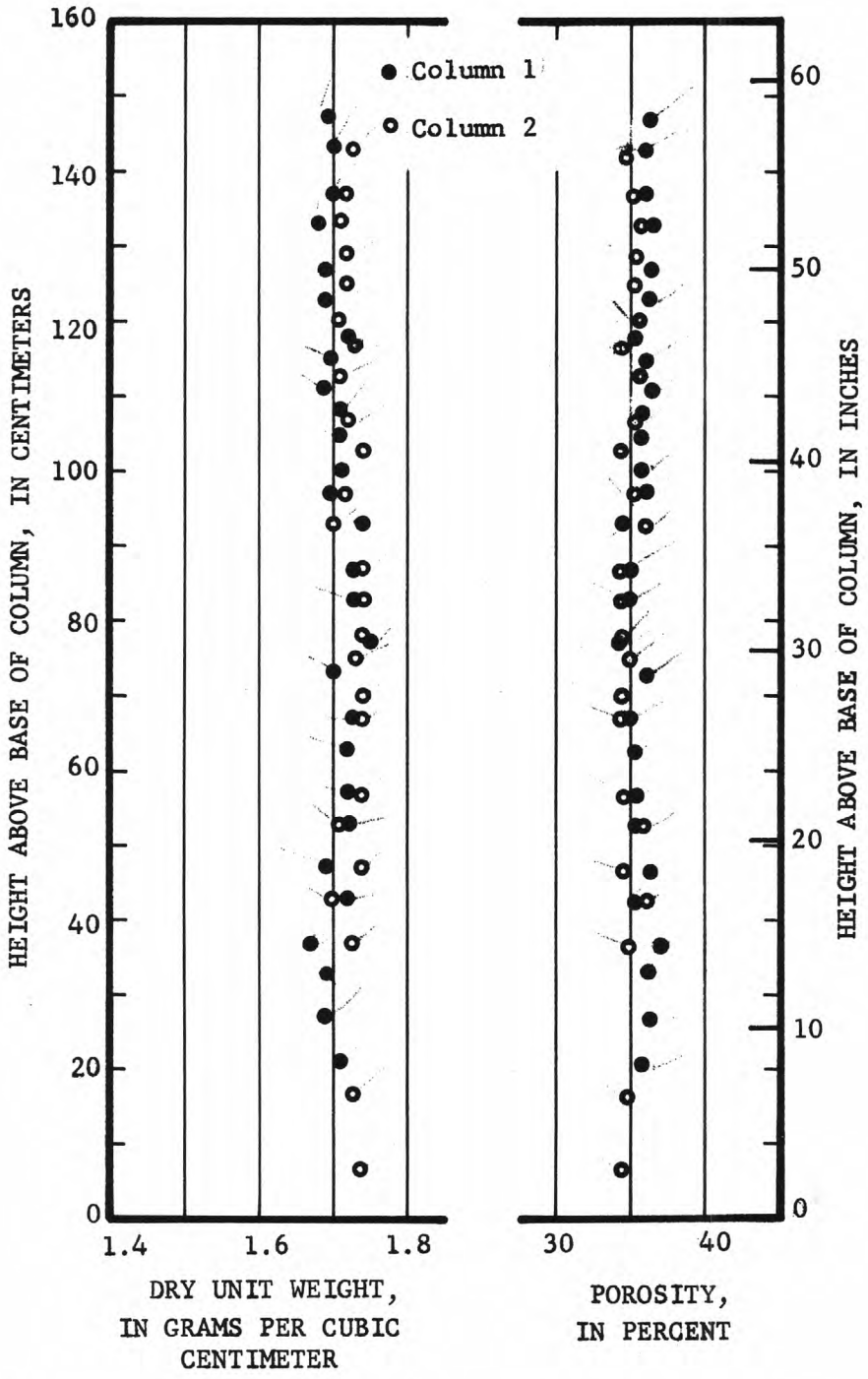


Figure 21.--Distribution of dry unit weight and porosity after draining columns of 20-mesh Del Monte sand.

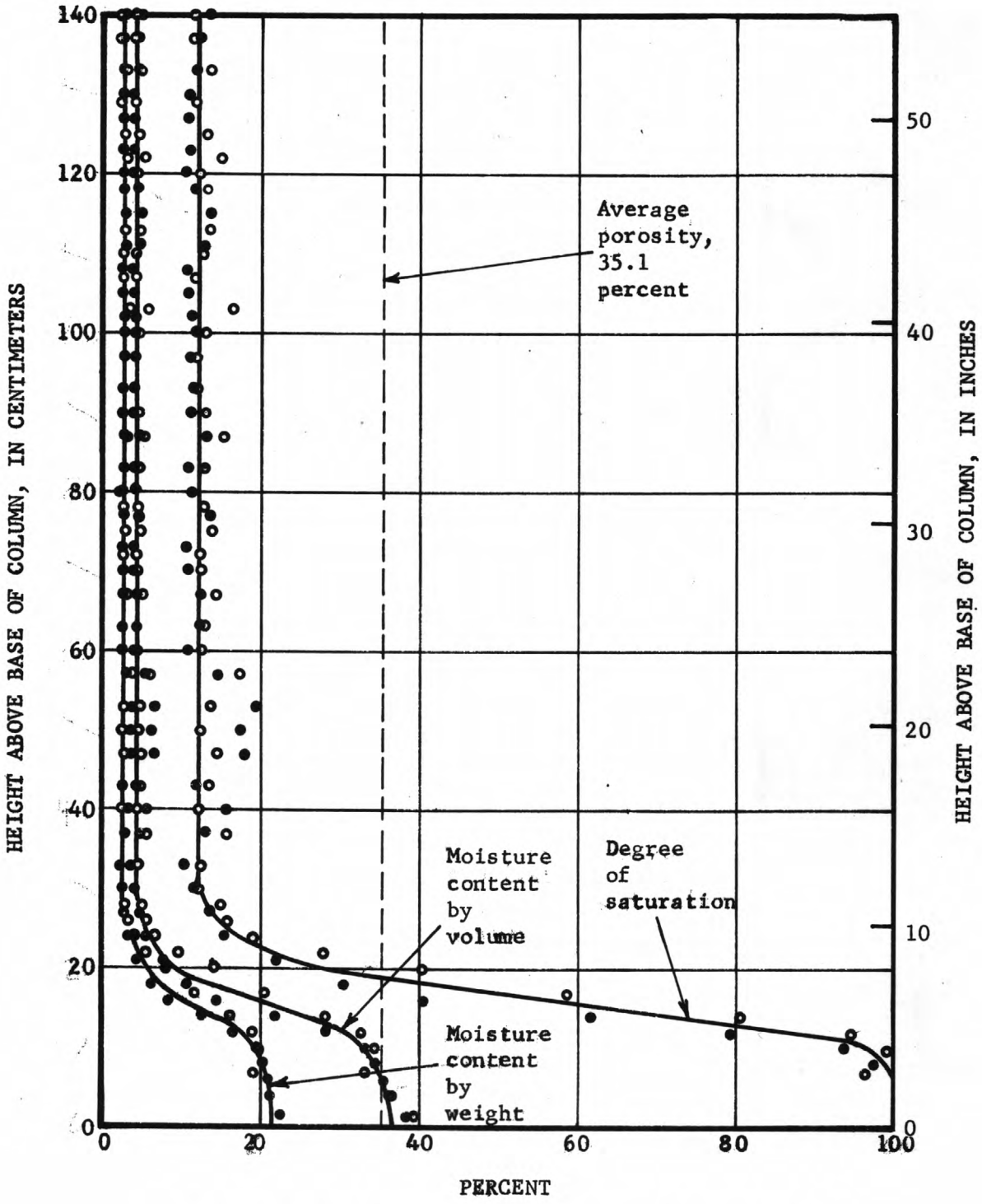


Figure 22.--Moisture retained after drainage of 20-mesh Del Monte sand.

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

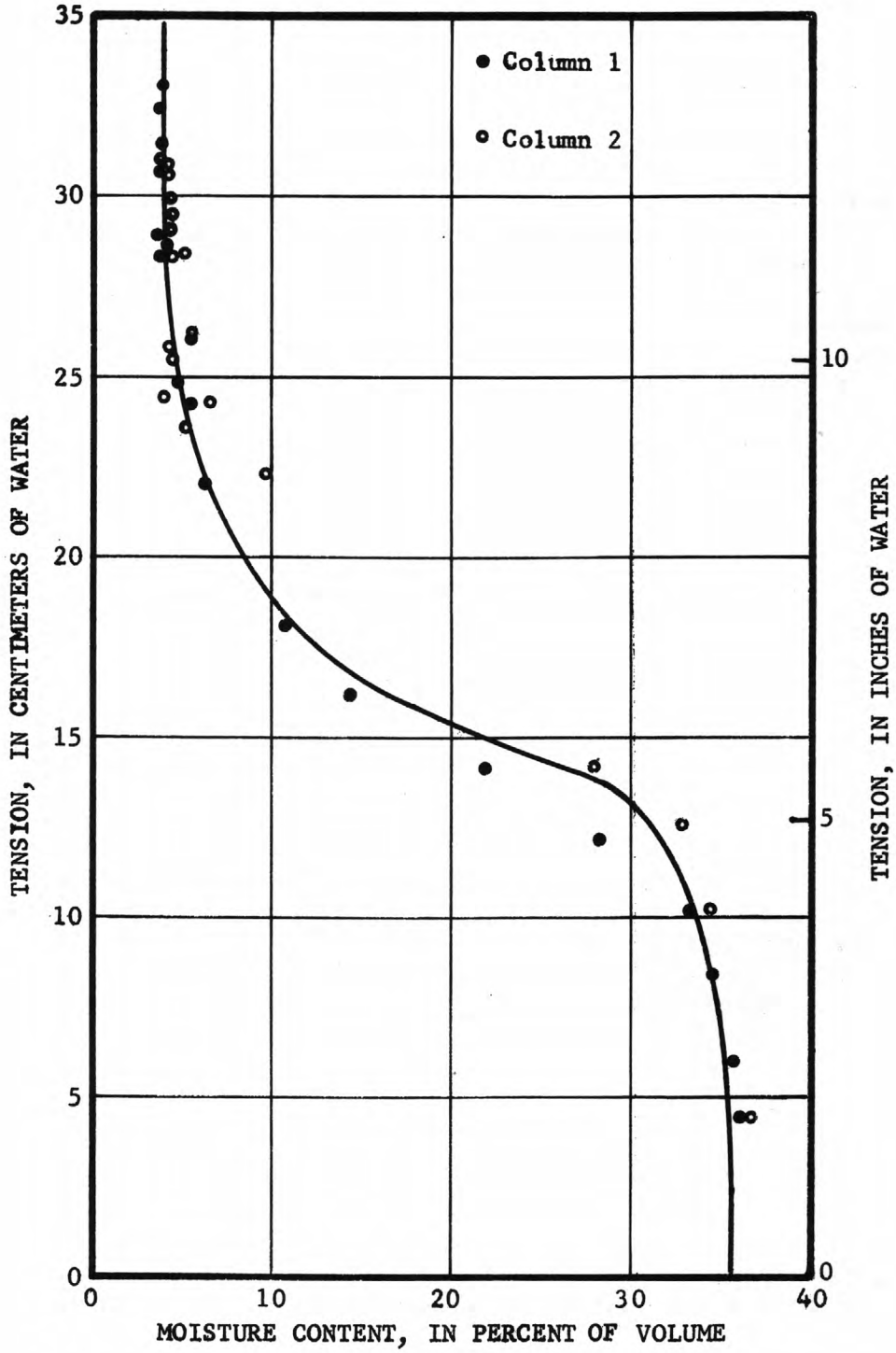


Figure 23.--Relation of moisture content to tension for 20-mesh Del Monte sand.

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 heterogenity, 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.

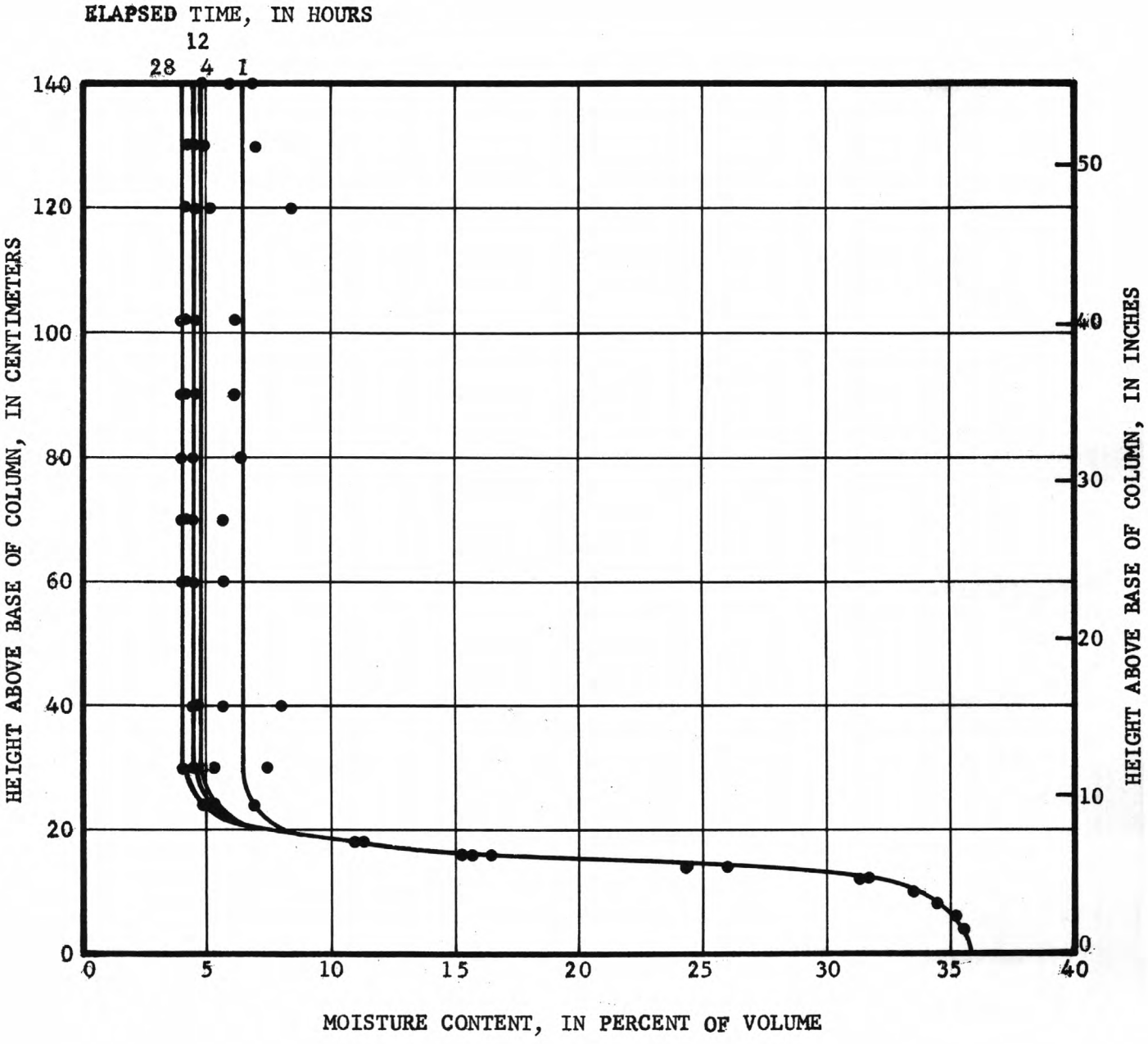


Figure 24.--Moisture distribution during drainage of 20-mesh Del Monte sand (column 1).

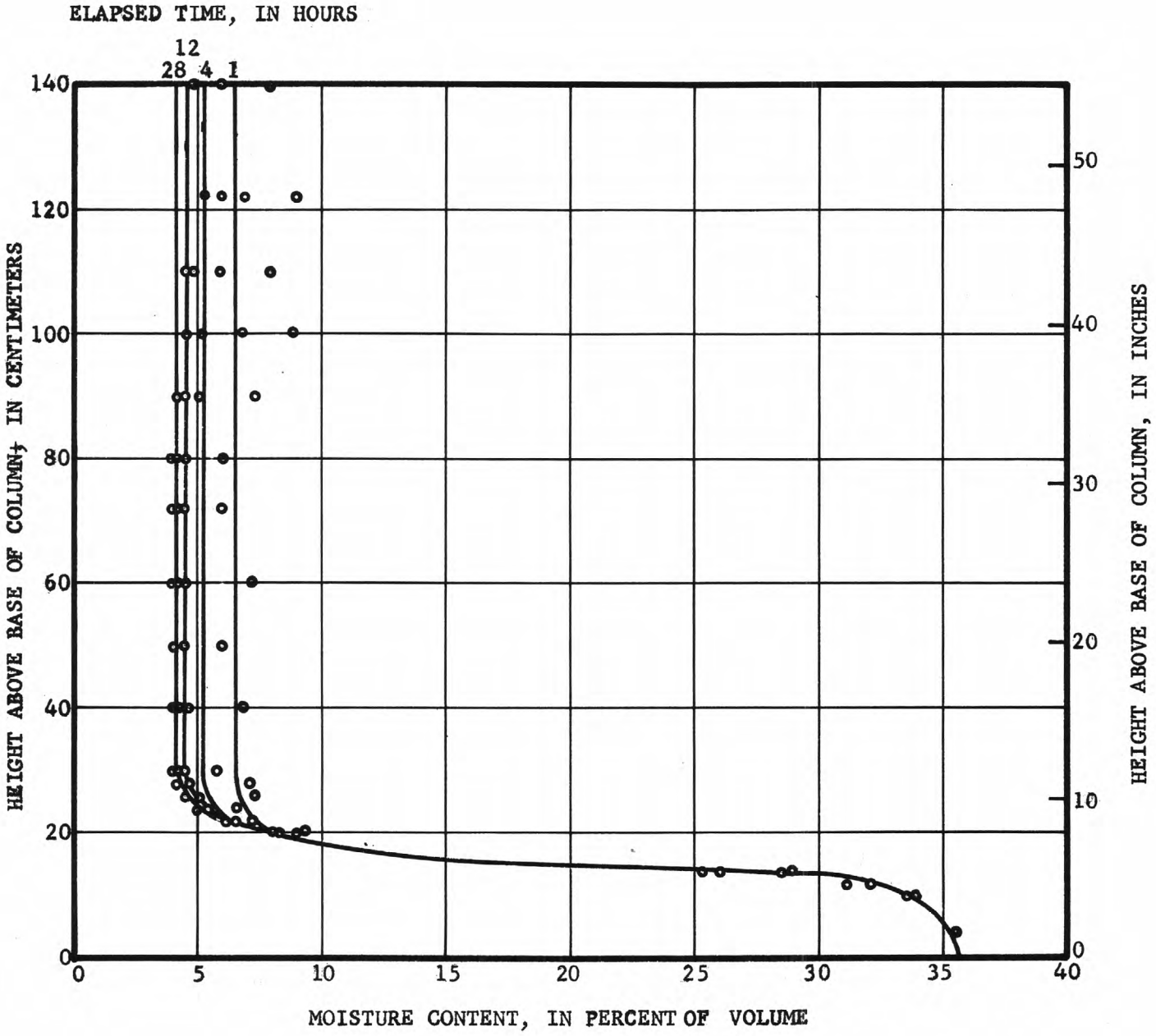


Figure 25.--Moisture distribution during drainage of 20-mesh Del Monte sand (column 2).

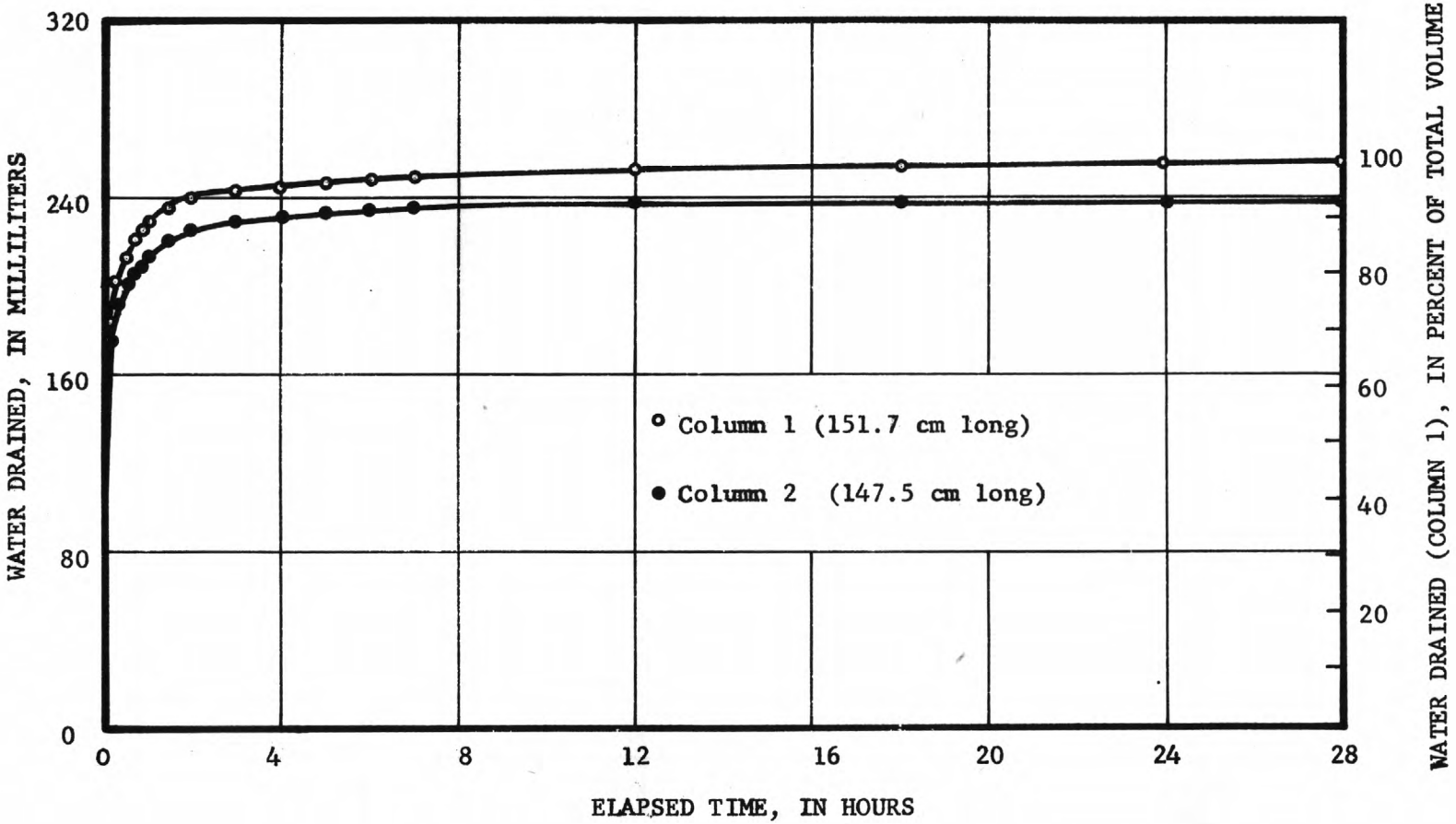


Figure 26.--Quantity of water drained from columns of 20-mesh Del Monte sand as related to time of drainage.

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.

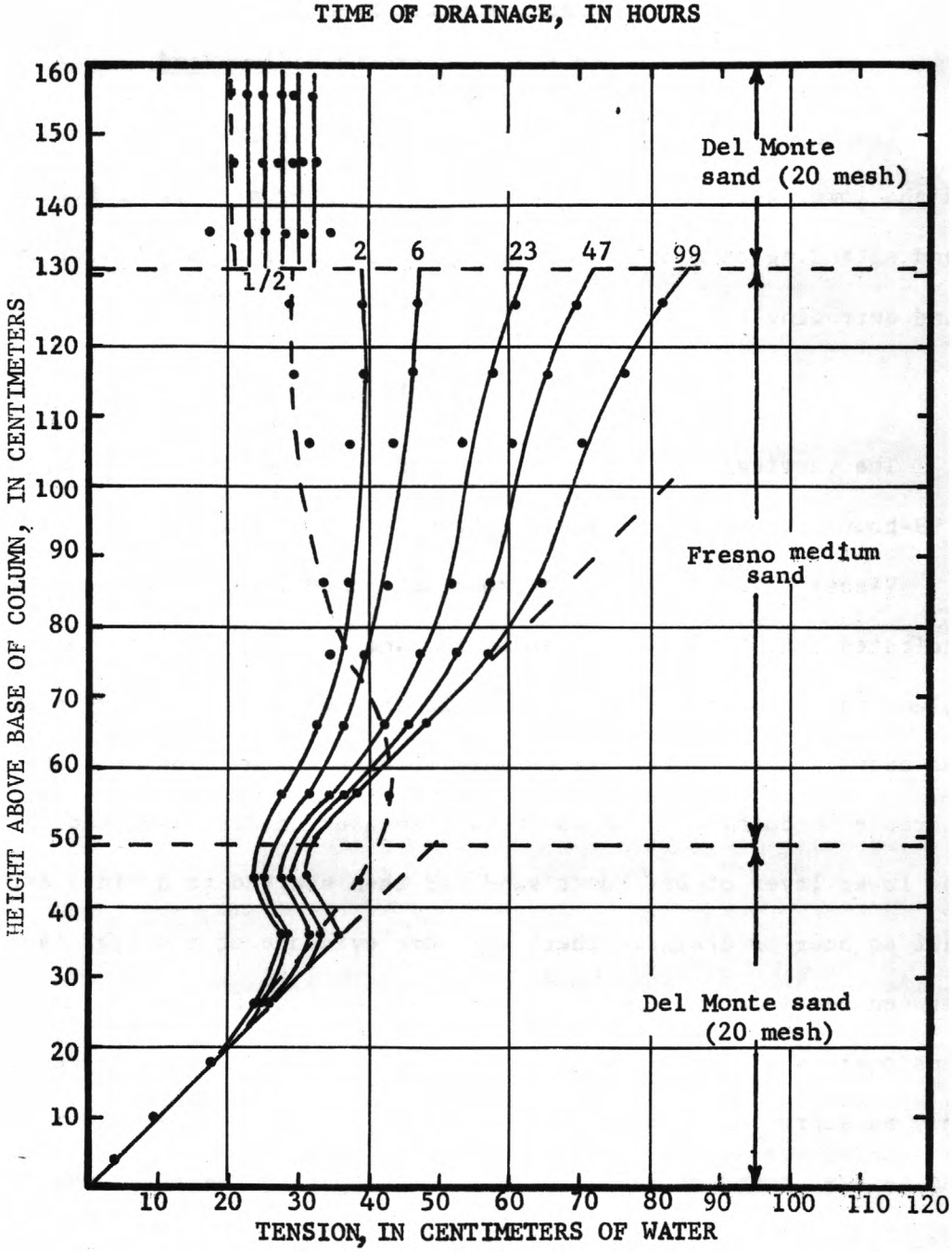


Figure 27.--Tension distribution with time of drainage in a stratified column.

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. 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 1 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).

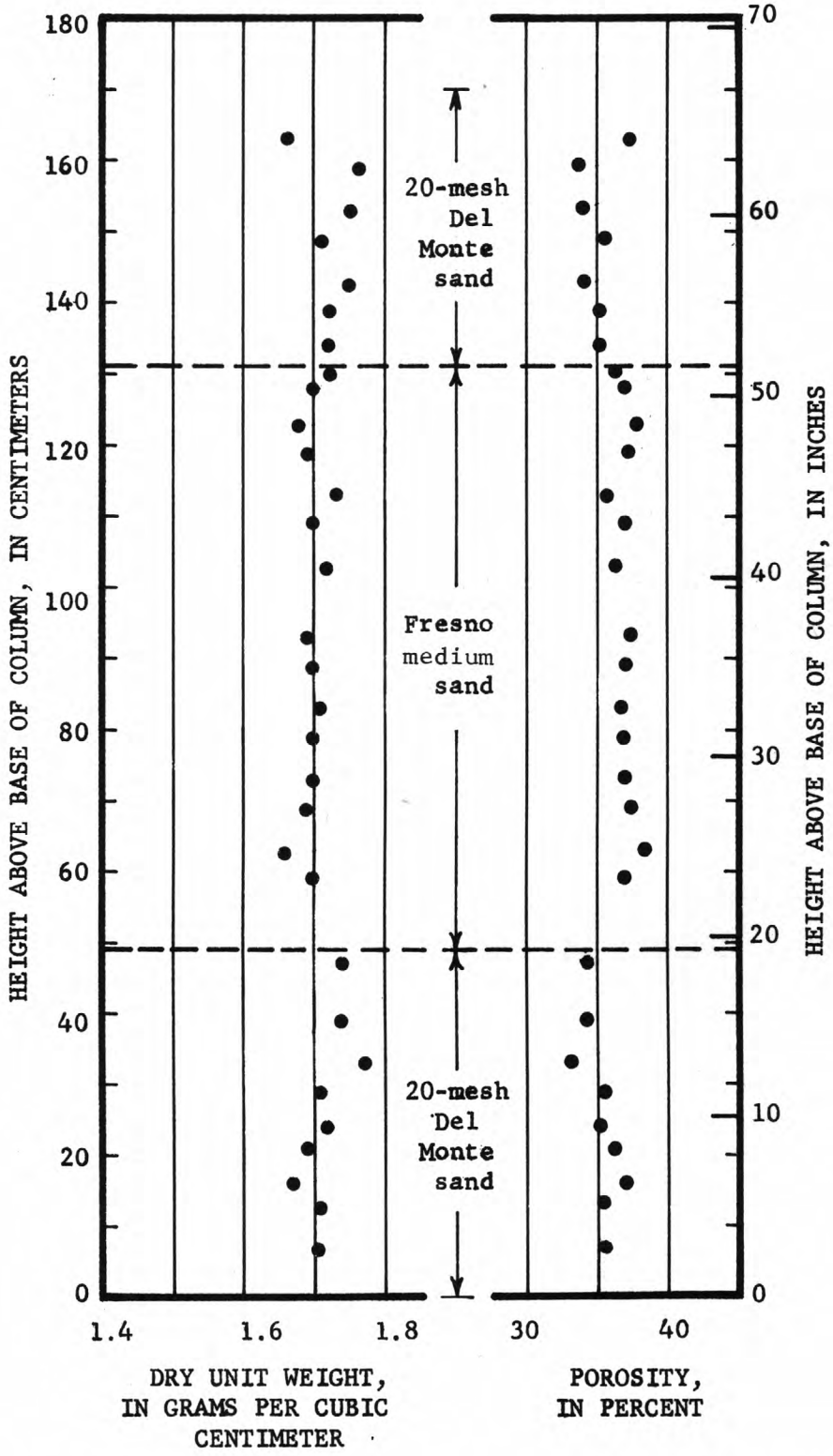


Figure 28.--Distribution of dry unit weight and porosity after draining a layered column of 20-mesh Del Monte sand and Fresno medium sand.

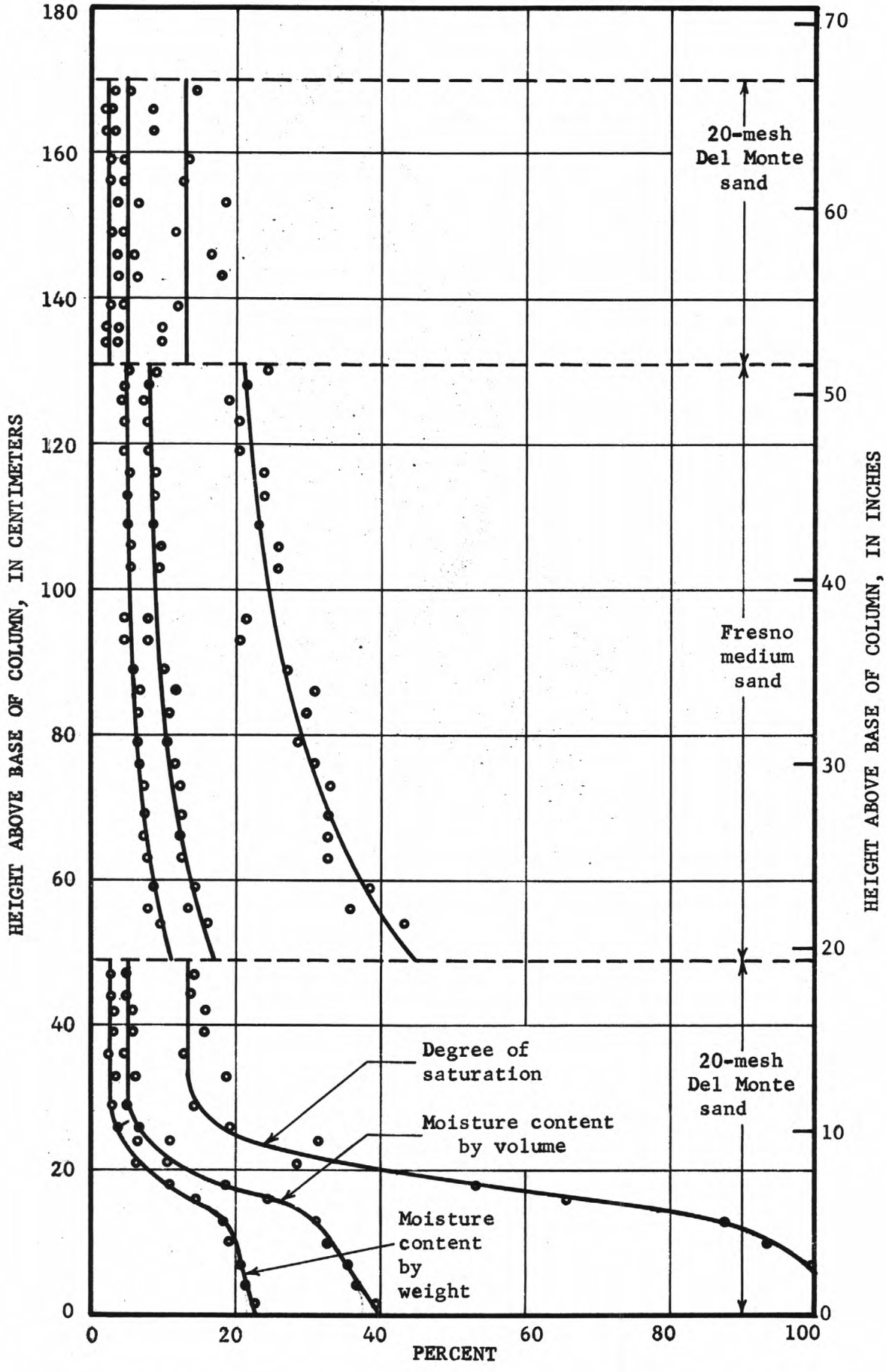


Figure 29.--Moisture retained after drainage of a layered column of 20-mesh Del Monte sand and Fresno medium sand.

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 curves 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.

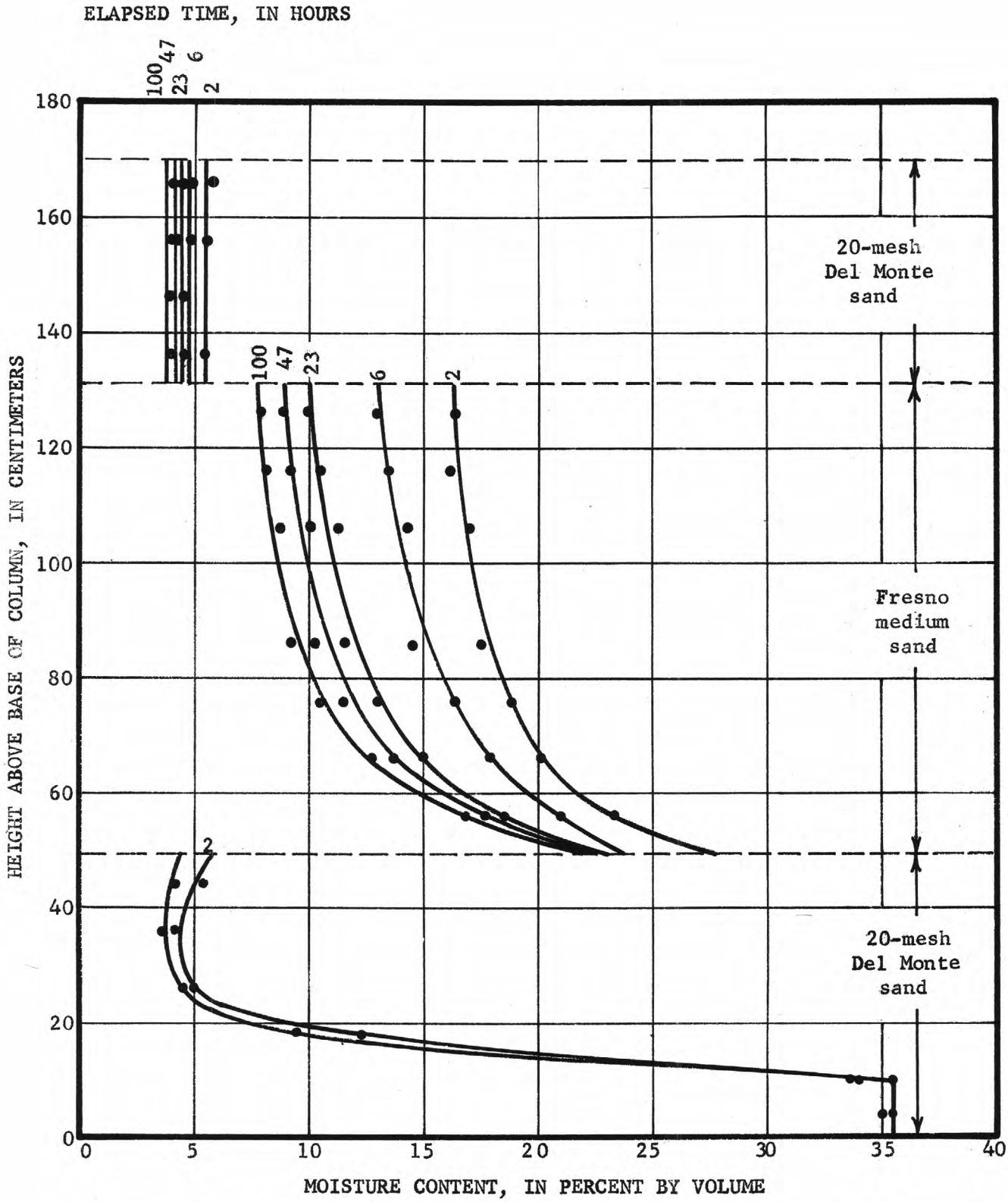


Figure 30.--Moisture distribution during drainage of a layered column of 20-mesh Del Monte sand and Fresno medium sand.

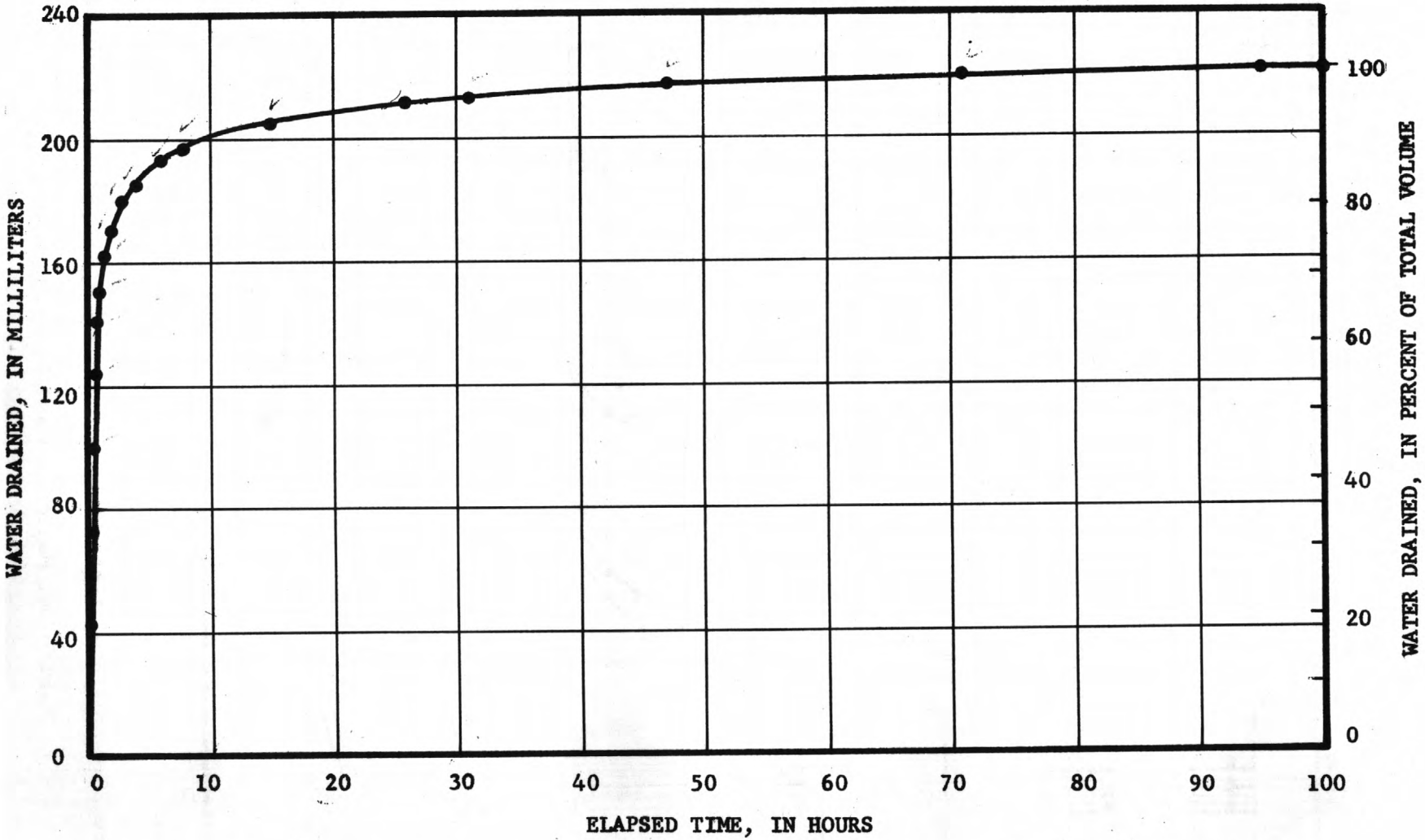


Figure 31.--Quantity of water drained from a layered column of 20-mesh Del Monte sand and Fresno medium sand.

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.

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.

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 but 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 1 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 the longer periods. However, it was believed that sufficient drainage 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. D-31-D-32.

Piper, A. M., and others, 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geol. Survey Water-Supply Paper 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. D-399-D-401.

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.

Versluys, Jan, 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.

GPO 847-02