DEPARTMENT OF SOILS INVESTIGATIONS

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CAPILLARITY TESTS BY CAPILLARIMETER AND BY SOIL FILLED TUBES

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SYNOPSIS

Results are presented from tests for height of capillary rise on eight samples typical of naturally graded soils—four gravels, three sands and one silt. Tests were conducted by two different methods: (1) capillarimeter or quick test indirect method; and (2) open soil filled tube or long time test direct method. The latter tests were continued for a period of over one year and gave much higher values of capillary rise for the finer soils than the capillarimeter tests. Observed rates of rise in the open tube tests did not agree with those computed from the theoretical equation. This is judged as due to the incompatibility between conditions in nature and the simplifying assumptions necessary for derivation of the theoretical equation.

The saturation of soils as water is drawn upward by capillarity is a well known phenomenon. It is a factor of considerable interest in studies of pavement performance and design as generally the introduction of a waterproof pavement over a soil subgrade by preventing evaporation allows the force of capillarity to exert its full effect in drawing water to the soil beneath the pavement. Certain present design practices consider capillarity in planning depth of under-drains particularly in soils subject to frost action (*1*).[1]

Capillarity tests covered here were conducted in the District Soils Laboratory, U. S. Army Engineer Office, Providence, R. I., to obtain information on likelihood of capillary saturation of subgrades in estimating the load capacity of several New England airports. Tests were conducted to determine the height of ultimate capillary rise and the rate of rise in eight typical soils (four gravels, three sands and one silt). These tests were originally started in June 1944 and were continued as a matter of interest for a period of slightly over one year at which time all samples but the silt had reached their ultimate rise.

MATERIALS

Eight typical soils were tested, each of which was chosen to represent a median gradation of the coarser grain size number bands of the Providence District Soil Classification (*2*) shown on Figure 1. Figure 2 shows gradation curves of the eight samples tested.

The original sample of Class 8 silt was a natural flood plain soil from Claremont, New Hampshire, but towards the end of the capillarity test additional material of very similar gradation from Union Village, Vt., was used in the upper portion of the open tube test. The remaining seven samples were artificially proportioned to give the desired gradation curves, using size fractions obtained by sieving a sandy gravel of largely rounded quartz aggregate obtained from Hillsgrove, R. I. In preparing the samples for the Classes 4 and 6 soils, the fraction passing the 200-mesh sieve was obtained from screening the above gravel—the grain size characteristics of these screenings having been determined by hydrometer analysis. For the Classes 5 and 7 soils, a silt from Keene, N. H., was similarly tested and used for the minus 200-mesh material.

Figure 3 shows the permeability characteristics of the eight materials which were determined by direct permeability tests with de-aired water after samples had been evacuated and then saturated under a vacuum. Apparent specific gravities are shown in Table 1 and were determined in evacuated

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[1] Italicized figures in parentheses refer to list of references at the end of the paper.

pycnometers as described by Casagrande and Fadum (*3*).

photograph of this apparatus with the test of Class 2 sand in progress is shown in Figure

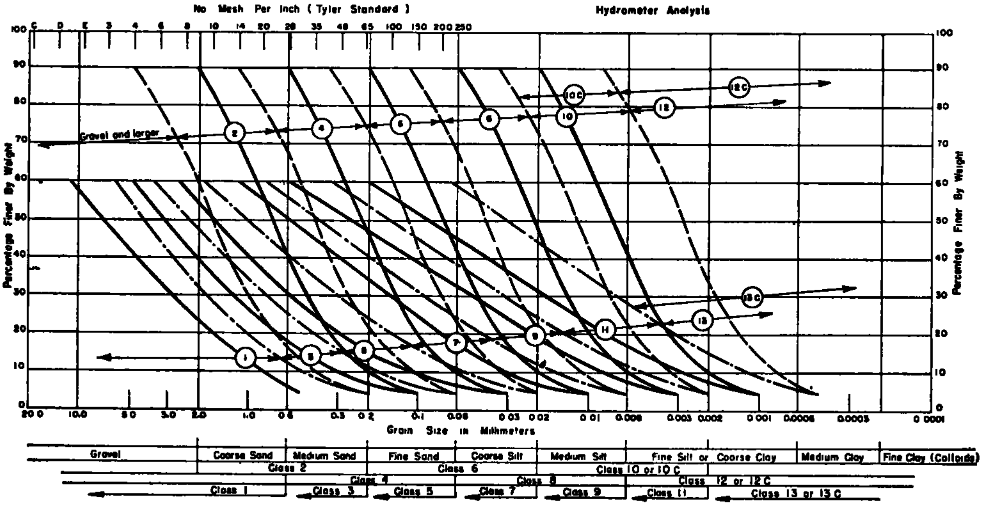


Figure 1. Diagram Showing Limits of Soil Classes—Providence District Soils Classification

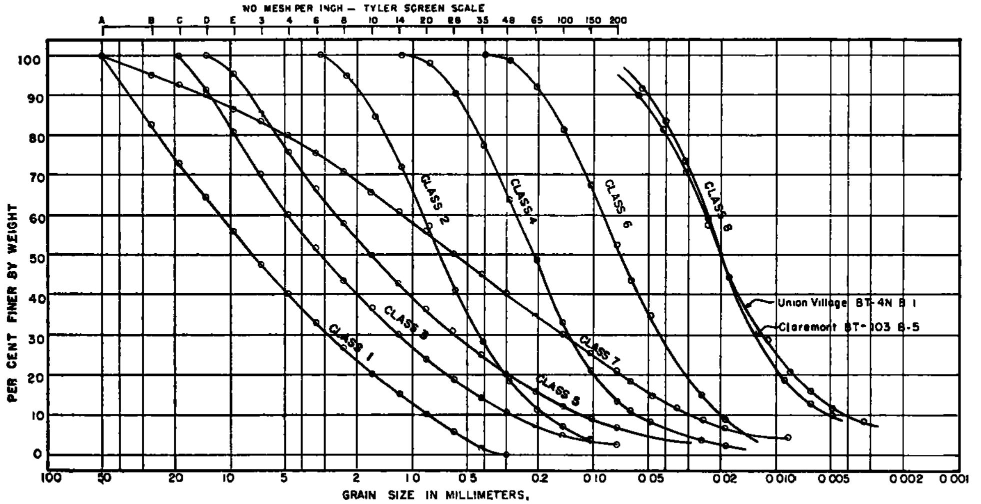


Figure 2. Gradation of Samples Tested

CAPILLARIMETER METHOD

This is a quick-test method and was conducted with apparatus similar to Beskow's Capillarimeter as adapted by the Public Roads Administration (*4*). Apparatus diagrams are shown in Figure 5 for both the PRA Capillarimeter and the modification used in these tests to permit larger and more representative samples of the gravels. A 4(a). In the capillarimeter the height of capillary rise is determined indirectly, being the maximum length of unbroken water column which can be suspended by the force of surface tension in the soil voids.

The soil sample was compacted in an air-dried condition to a density corresponding to natural deposition. Sample was then evacuated and while still under vacuum was

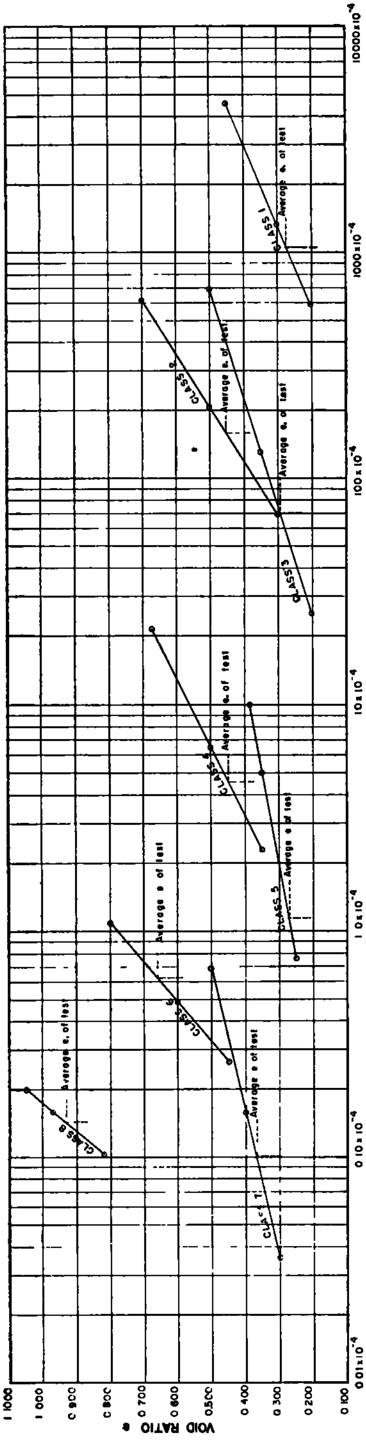
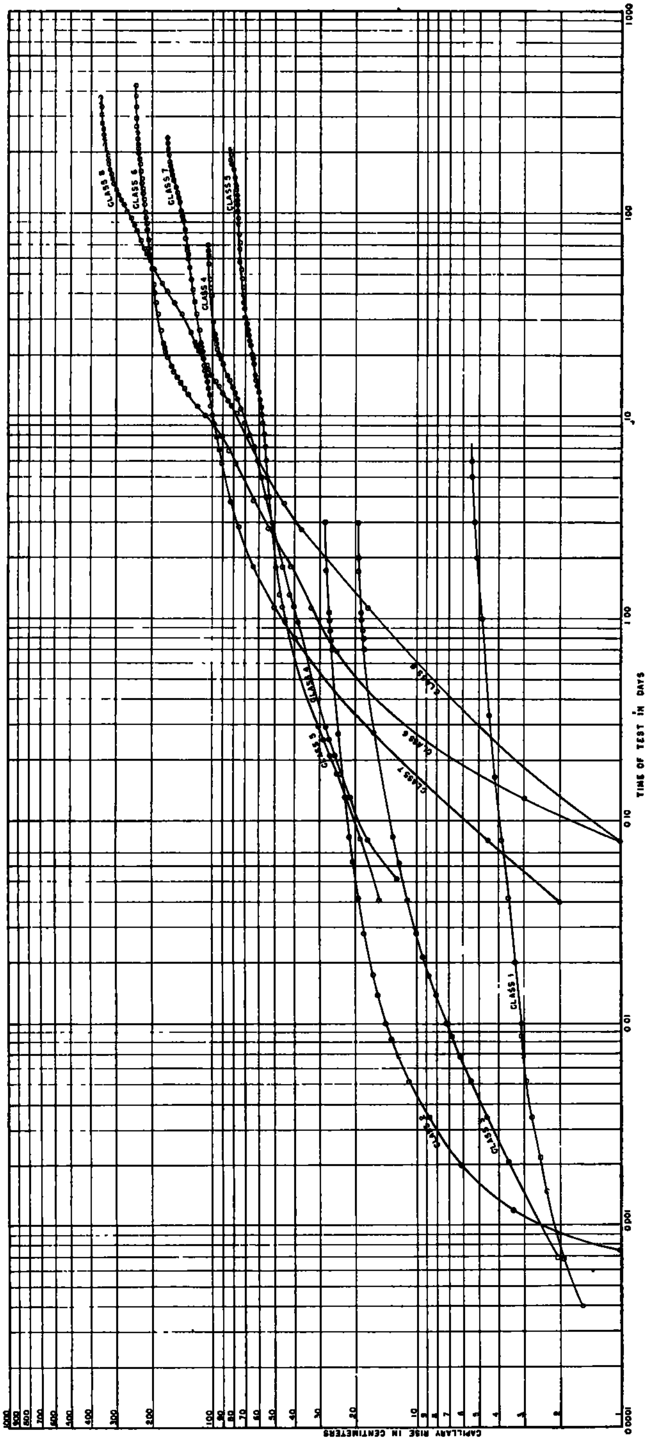


Figure 3. Permeability—Void Ratio Curves



saturated from the bottom until free water appeared on the top of the sample. De-aired water was used for saturation, prepared by spraying into a high vacuum as described by Bertram (*5*). The vacuum was then released and the acting hydraulic head was lowered in increments of 2 cm at 5-min intervals until air bubbles appeared on the perforated disc at bottom of sample, indicating a continuous air-channel from top to bottom of the saturated sample. The vertical distance from the free water surface in the constant head device to top of the sample was measured as the height of capillary rise, h_c.

TABLE 1
CAPILLARITY TEST RESULTS

Sample Class No.	Specific Gravity	Effective Size—d_{10}	Capillarimeter Tests				Open Tube Tests			
			Void Ratio[a] e	Dry Density	Capillary Rise	Permeability[b] $k \times 10^4$	Void Ratio[a] e	Dry Density	Capillary Rise	**Permeability[b] $k \times 10^4$**
		mm		*lb per cu ft*	*cm*	*cm per sec*		*lb per cu ft*	*cm*	***cm per sec***
1	2.70	0.82	0.27	132.2	6.0	1100	0.27	132.2	5.4	**1100**
2	2.65	0.20	0.45	114.8	20.0	160	0.45	113.8	28.4	**160**
3	2.70	0.30	0.29	130.2	20.0	71	0.29	130.2	19.5	**71**
4	2.70	0.06	0.45	116.4	68.0	4.6	0.45	116.4	106.0	**4.6**
5	2.69	0.11	0.27	132.0	60.0	1.1	0.27	132.2	82.0	**1.1**
6	2.75	0.02	0.48	116.1	120.0	0.29	0.66	103.3	239.6	**0.62**
7	2.77	0.03	0.36	126.7	112.0	0.096	0.36	126.5	165.5	**0.096**
8	2.76	0.006	0.95	88.3	180.0	0.15	0.93	89.3	359.2	**0.14**

[a] Void ratio shown is overall value for entire sample.
[b] Permeability coefficient taken from k-e curves at overall void ratio shown.

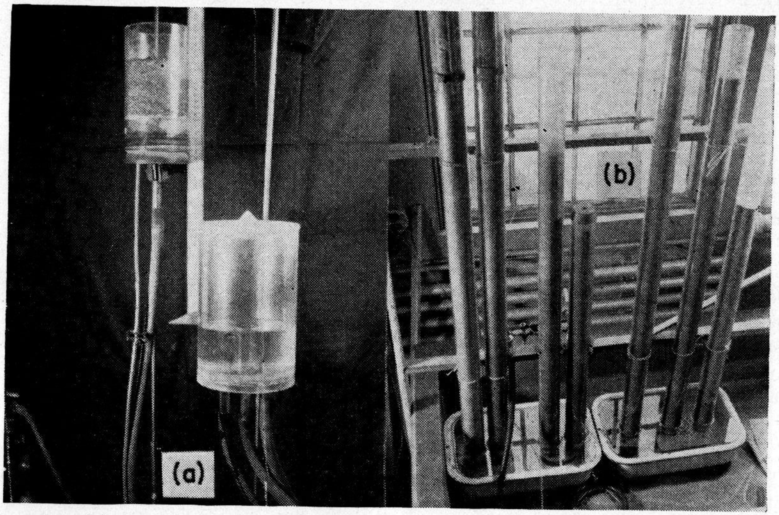


Figure 4. (a) **Capillarimeter.** (b) **Open Tube Tests—Longer tubes show splices**

OPEN TUBE METHOD

This is a long-time test in which the height of capillary rise in a soil-filled tube is measured directly. Apparatus consisted of 2- and 4-in. diameter soil-filled tubes of transparent plastic (Lucite), the bottoms of which were closed with a perforated brass plate, screen, and cloth, and rested on supports in a pan of water to an approximate depth of 2 in. These tubes are shown in the photograph in Figure 4(b).

Samples were compacted air-dried into the tubes, using a round hardwood rammer accompanied by tapping the sides of the tubes with a mallet. Compaction planes at the top of each layer were scarified before adding the following layer. Compaction sought was the same density obtained in the capillarimeter tests to make the results comparable. As shown by the tabulated densities on Table 1 this object was closely attained for all samples except the Class 6. The soil-filled tube was then set in a pan of tap water, with care not to trap an air pocket under the brass plate and the test was started. Readings were taken hourly for the first day, then daily, and finally weekly until completion of the test. The rise in each case was measured from the free surface of the water in the pan to the wetted line in the soil-filled tube. With the exception of the Class 8 silt, tests were continued until height of the wetted line appeared to remain constant in a plot of height against time. When it became apparent that capillary rise would exceed the height of soil in any tube, additional soil was added, attempting to obtain the same compaction. In the tests of the Classes 6, 7 and 8 samples, an additional length of tubing was joined to the original length with clamps and plastic cement to form an airtight connection.

It was found that the capillary action resulted in additional compaction due to the weight of the suspended water column being transmitted to the soils. This occasionally resulted in an air gap where the soil column pulled apart which could usually be remedied by tapping on the tube near the gap to close it. One gap near the top of the Class 8 silt opened below the wetted line; the soil was then removed above the gap, air-dried, and recompacted; and a correction was made in the time readings. At the conclusion of tests of the finer materials, the soil was removed from the tubes with a small soil auger in measured increments, from which water content, percent of saturation and void ratio data were obtained.

HEIGHT OF CAPILLARY RISE

Heights of capillary rise by the two test methods are given in Table 1 and are shown graphically on Figure 6. Figure 7 (p. 462) shows the rate of rise. The water content, percent saturation and density data obtained by dismantling the open tube tests are shown on Figures 8 to 11 inclusive. In each case the height of rise is greater in the open tube than that shown by the capillarimeter. This is shown graphically on Figure 6 where h_c is plotted against Hazens effective size (the 10 percent size, d_{10} = the size where 10 percent passes and 90 percent is retained). The finer the soil the greater is the difference between results of the two test methods. Curves of the same general shape as on Figure 6 were also obtained by plotting h_c against the coefficient of permeability, k, corresponding to the average void ratio, e, of the test sample.

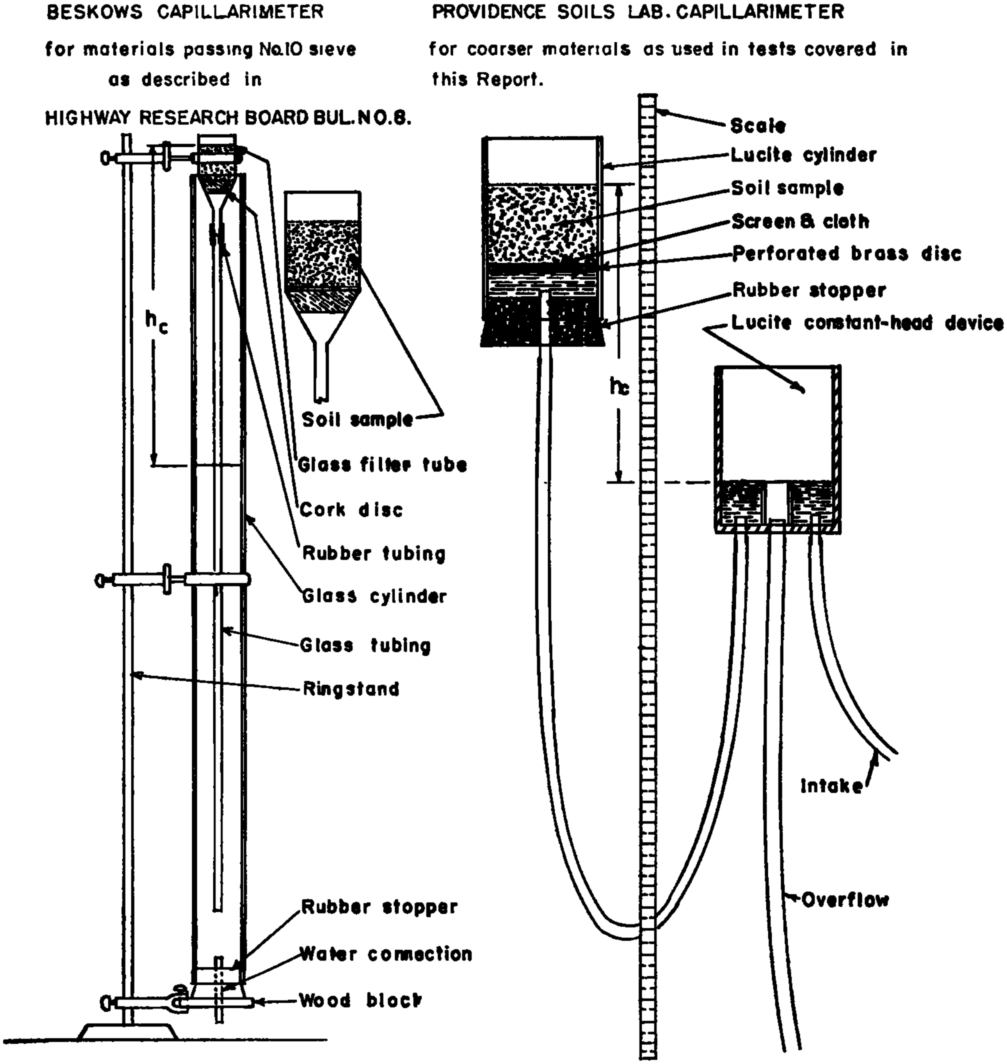
The value from the capillarimeter or quick-test method is considered the passive capillary rise which is controlled mainly by the large voids in the soil. In these larger voids capillary tension is the least and, accordingly releases first causing a break in the suspended water column. Contrastingly, the open-tube method or long-time test determines the active capillary rise which is influenced by all the void sizes in the soil. Here, capillary tension is much greater as it is controlled by the smaller voids and accordingly causes a much higher rise.

Within limits of the soils investigated Figure 6 indicates that capillary rise, particularly active rise, increases markedly with the finer grained soils. This is at variance with conclusions reached by Valle-Rodas (*6*) that height of passive capillary rise might be expected to exceed that of active capillary rise in finer grained soils. However, the tests of Valle-Rodas were conducted on quite artificial materials consisting of sand fractions prepared by screening between successive sizes of sieves. Contrastingly, the tests presented here attempted to cover soil gradations typically found in nature.

VARIATION OF WATER CONTENT WITH HEIGHT

Bar graphs of Figures 8 to 11 inclusive show variations with height for water content, saturation, and density at end of test. Water content and density were measured directly while the saturation percentage is a computed value of lower accuracy, as small errors in measurement of density and in determination of specific gravity contribute much larger errors in the percent saturation. The practical difficulties of compacting the soil to a uniform density over long lengths of tubing are also illustrated.

For the uniform soils, Classes 6 and 8, high and reasonably constant values of water content and percent saturation show generally up to a certain height above which they steadily decrease. This agrees with other investigations as summarized by


BESKOWS CAPILLARIMETER
for materials passing No.10 sieve
as described in
HIGHWAY RESEARCH BOARD BUL. NO.8.

PROVIDENCE SOILS LAB. CAPILLARIMETER
for coarser materials as used in tests covered in
this Report.

Figure 5. Diagrams of Apparatus

Terzaghi (7). For variably graded soils, Classes 5 and 7, the zone of constantly high saturation is much less definite and the zone of steadily decreasing saturation covers a much greater part of the capillary rise height. This is probably due to much greater irregularity in the void pattern of these variably graded soils than in the uniformly graded soils.

Heights of passive capillary rise as determined by the capillarimeter and plotted on the bar-graphs of Figures 8 to 11 inclusive, are roughly of magnitude similar to the lower zone of high saturation. From reasoning that the passive capillary rise is controlled by larger voids an approximate agreement might be expected although most tests examined, including those reported by others, generally have shown the zone of high saturation less than the height of passive capillary rise.

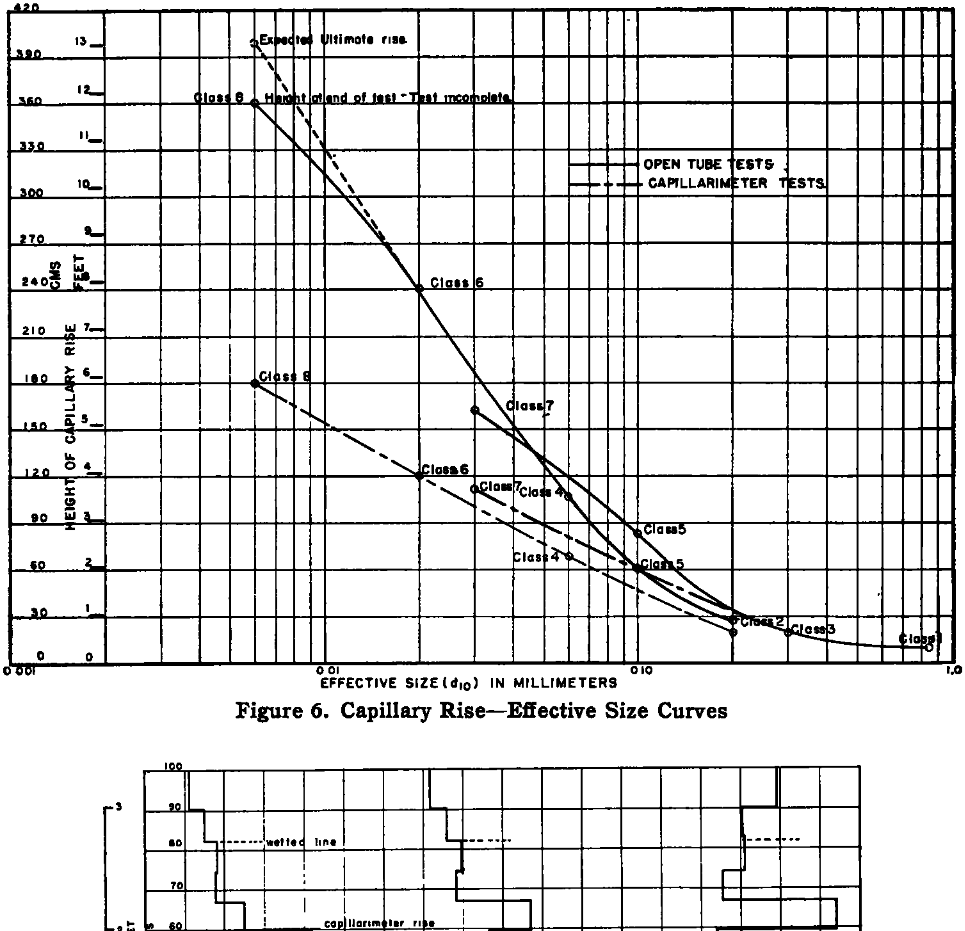


Figure 6. Capillary Rise—Effective Size Curves

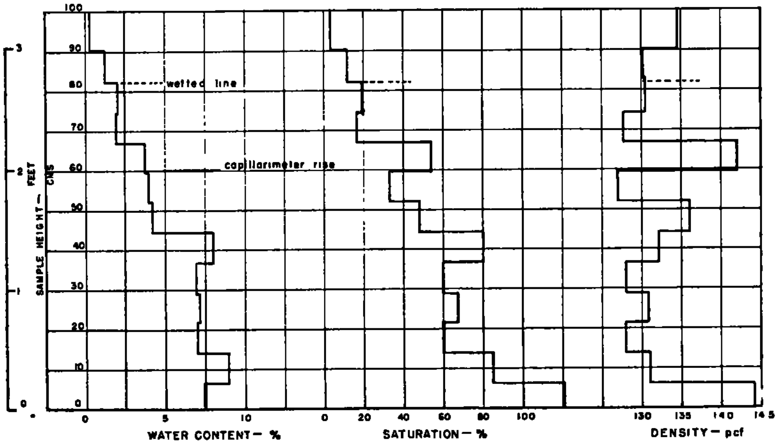


Figure 8. Water Content, Saturation, and Dry Density at End of Test—Class 5

FACTORS CONTRIBUTING TO IRREGULARITIES IN THE DATA

The following factors probably contributed to irregularities in the observed data:

1. Uniform compaction was not obtained over the entire length of the sample and probably even greater variations existed in parts of each increment. In all actual soils irregularities in void pattern are to be expected especially in the variably graded soils which contain appreciable coarse aggregate.

2. Evaporation undoubtedly occurred in the open tube tests as the soil surface was generally maintained only 6 to 18 in. above the wetted line, whereas desiccation has been observed to depths of over 20 ft. in certain soils of Texas and probably extends to greater depths in more arid climates. The capillarimeter quick tests were conducted in June 1944 with room temperature about 90 F. The open tube tests continued throughout the year with a temperature range of 40 to 100 F. and tops of the tubes were generally located in the drier atmosphere near the ceiling. With reasonably constant temperature the effect of evaporation would be to retard the rate of rise. Under conditions of varying temperature, moisture vapor would condense as temperature falls. This would give the appearance of an acceleration in the rate of rise with the reverse occurring as temperature rises. In either case mois-

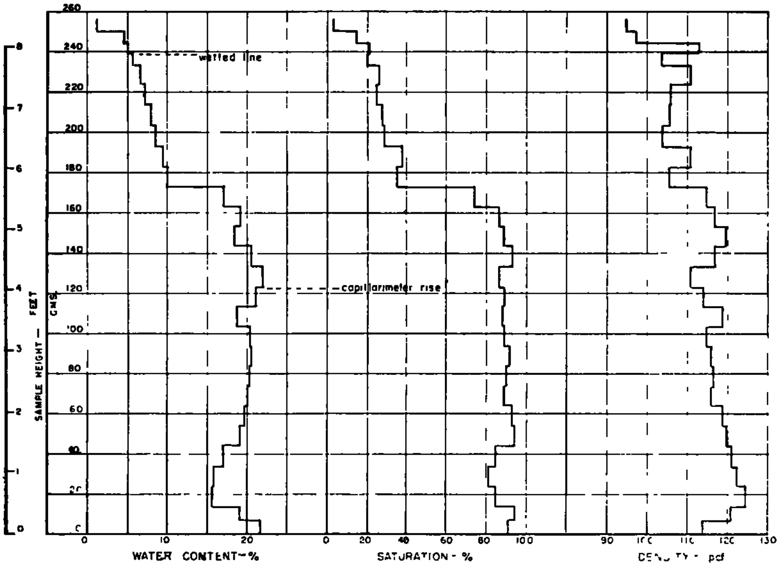


Figure 9. Water Content, Saturation, and Dry Density at End of Test—Class 6

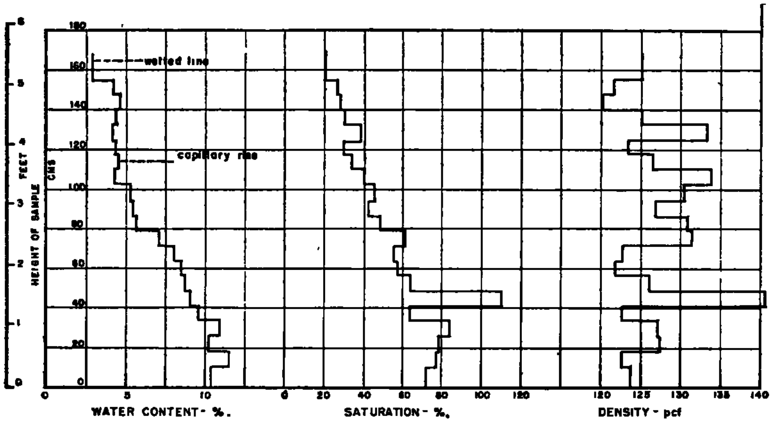


Figure 10. Water Content, Saturation, and Dry Density at End of Test—Class 7

ture vapor should be expected above the wetted line and is probably represented by the small values of water content measured above the wetted line on dismantling the tests as plotted on the bar-graphs of Figures 8 to 11 inclusive.

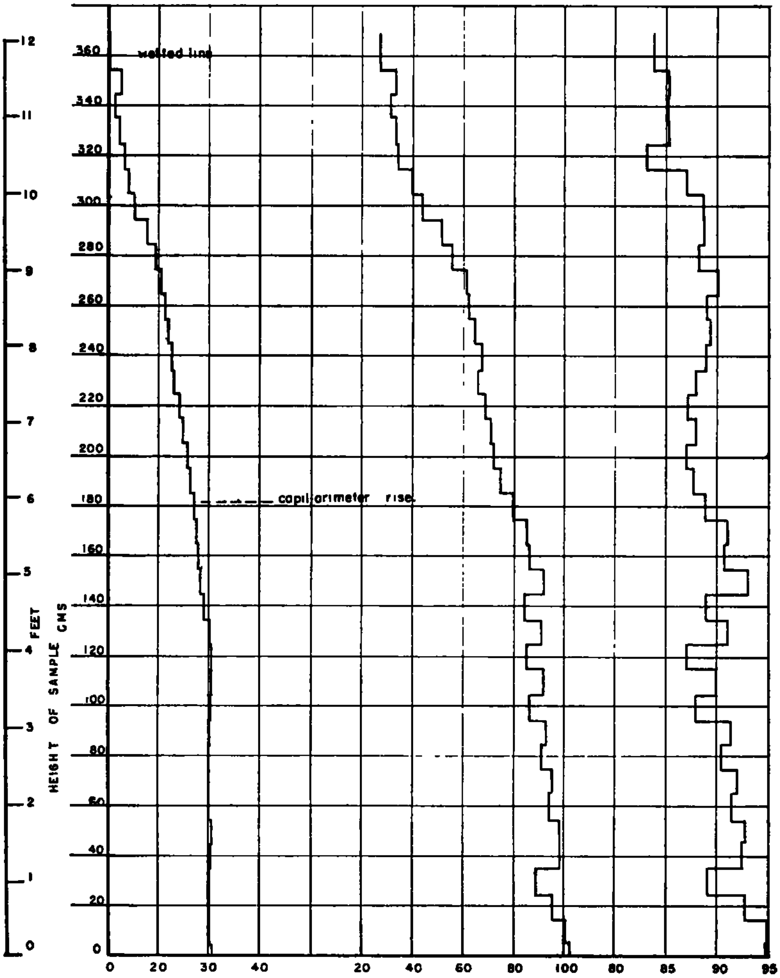


Figure 11. Water Content, Saturation, and Dry Density at End of Test—Class 8

3. Like most untreated waters the tap water used for the open tube tests contained appreciable dissolved air, some of which would be deposited in the soil, thereby decreasing the saturation of the soil and its permeability. This would be accentuated by a temperature gradient rising through the sample as the solubility of air is less in warm water than in cool water. Although not covered by measurements a temperature gradient rising upward through the soil probably occurred. Due to cooling by surface evaporation, temperature of water in the pan would be expected to be lower than that of the adjacent soil and water in the tube and progressing toward the ceiling, the usual rise in air temperature undoubtedly occurred. The major effect of air deposition would be to retard the rate of rise.

THEORETICAL RATE OF CAPILLARY RISE

Figures 12 to 16 inclusive show comparisons of the observed time-rise curves from the long tube tests with theoretical curves computed from the solution given by Terzaghi (*8*). While the curves are of similar shape, the actual rate of rise in the test is much smaller than the theoretical. Deposition of dissolved air from the tap water used in the long tube test is considered mainly responsible for the discrepancy as effects of entrapped air are to decrease the effective porosity (and its companion function, void ratio) and to greatly decrease the permeability. The value of $k = 4.6 \cdot 10^{-4}$ cms per sec was obtained in a direct permeability test using de-aired water from which the dissolved air had been substantially removed. From many permeability tests it has been conclusively demonstrated that small amounts of entrapped air cause very great reductions in the coefficient of permeability. Possible decrease in void ratio, e, from entrapped air is relatively small and therefore the main effect to be considered in the theoretical formula is the change in k. Neglecting minor effect of small changes in e, the theoretical curve can be matched with the observed curve at the point $\frac{h_c}{2}$ by recomputing the theoretical curve with an

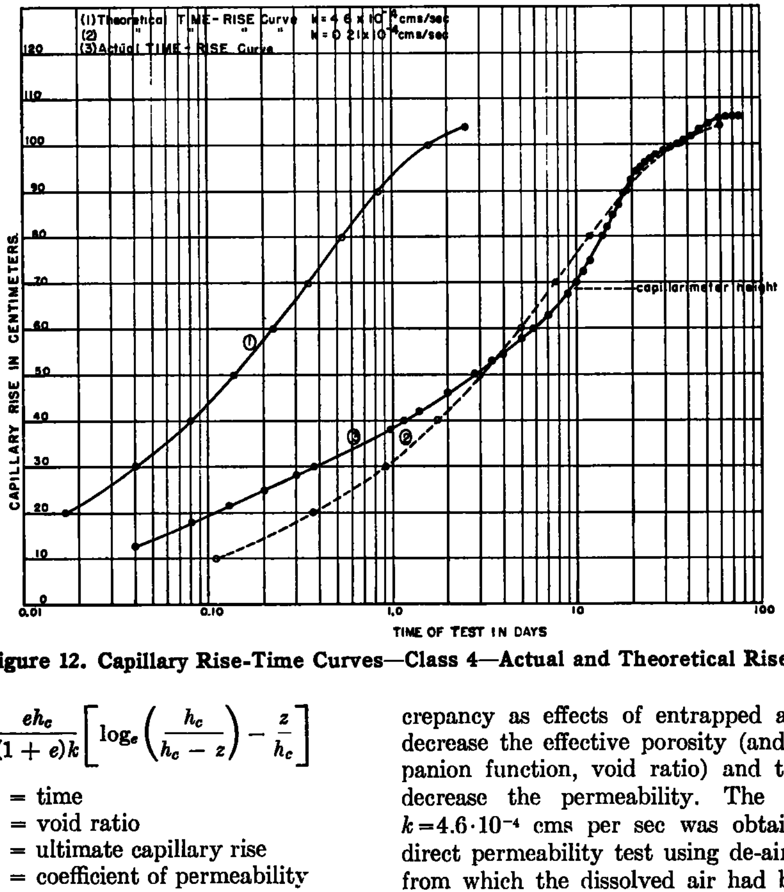


Figure 12. Capillary Rise-Time Curves—Class 4—Actual and Theoretical Rise

$$t = \frac{eh_c}{(1+e)k}\left[\log_e\left(\frac{h_c}{h_c - z}\right) - \frac{z}{h_c}\right]$$

wherein t = time
e = void ratio
h_c = ultimate capillary rise
k = coefficient of permeability
z = height of rise at time t

This solution is based on a necessary simplifying assumption that the soil column is completely saturated below height z and completely dry above there. Further conditions are constant values of e and k throughout the soil column and throughout the period of capillary rise.

Figure 12 shows the actual time-rise curve observed for the Class 4 sand. To the left is shown the theoretical curve computed using the values of h_c as observed, and overall average e with corresponding k value ($4 \cdot 6 \cdot 10^{-4}$ cms per sec), from Table 1. While

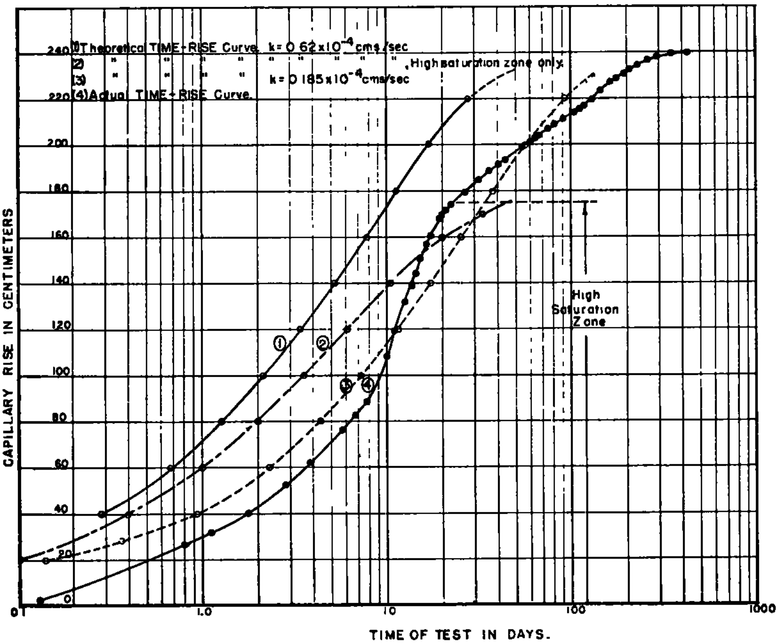


Figure 13. Capillary Rise-Time Curves—Class 6—Actual and Theoretical Rise

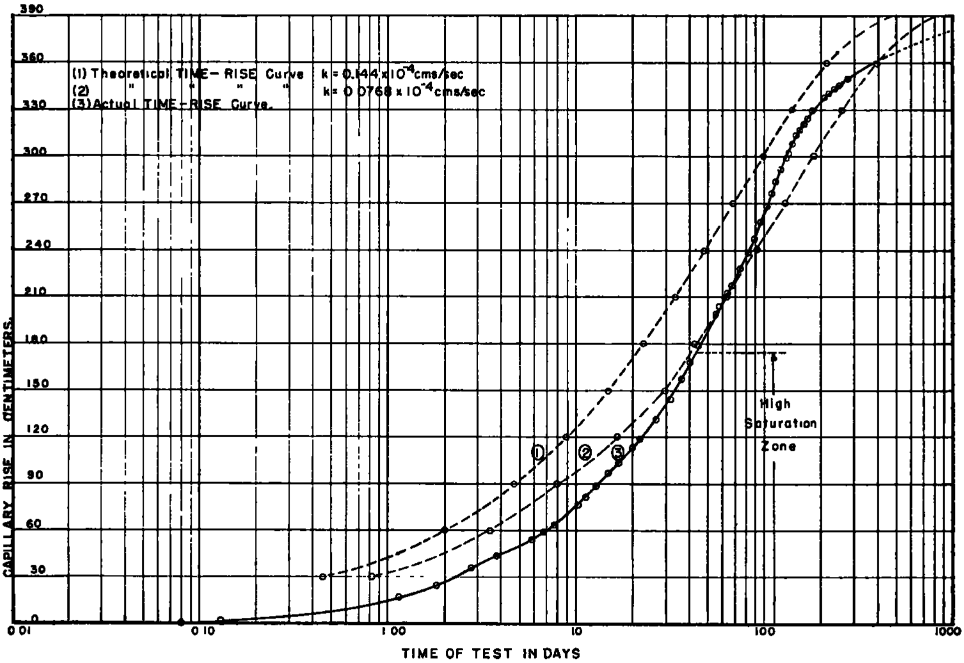


Figure 14. Capillary Rise-Time Curves—Class 8—Actual and Theoretical Rise

effective value of $k = 0.21 \cdot 10^{-4}$ cms per sec. This latter value is less than $\frac{1}{70}$ the value of k determined by direct permeability test with de-aired water and gives a measure of the reduction caused by the entrapped air in the Class 4 material in the long tube.

With the two curves thus matched at the point $\frac{h_c}{2}$ there is approximate agreement between the theoretical and observed curves for the Class 4 sample as shown on Figure 12. By likewise matching the two curves for the Class 6 and Class 8 samples similar approximate agreement is shown on Figures 13 and 14. Apparent reductions from values of k by tests with de-aired water are less in these latter two cases—approximately $\frac{1}{4}$ for the Class 6 sample and $\frac{1}{2}$ for the Class 8 sample.

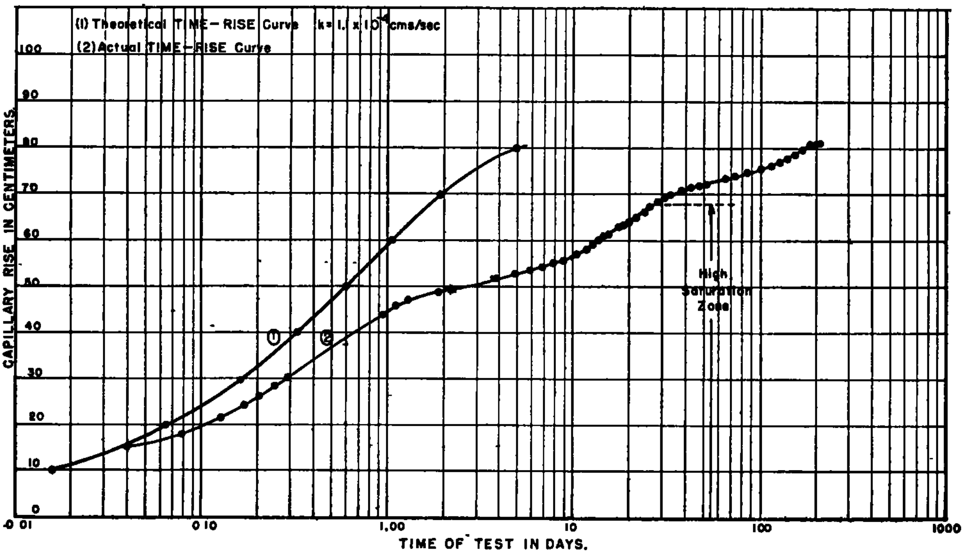


Figure 15. Capillary Rise-Time Curves—Class 5—Actual and Theoretical Rise

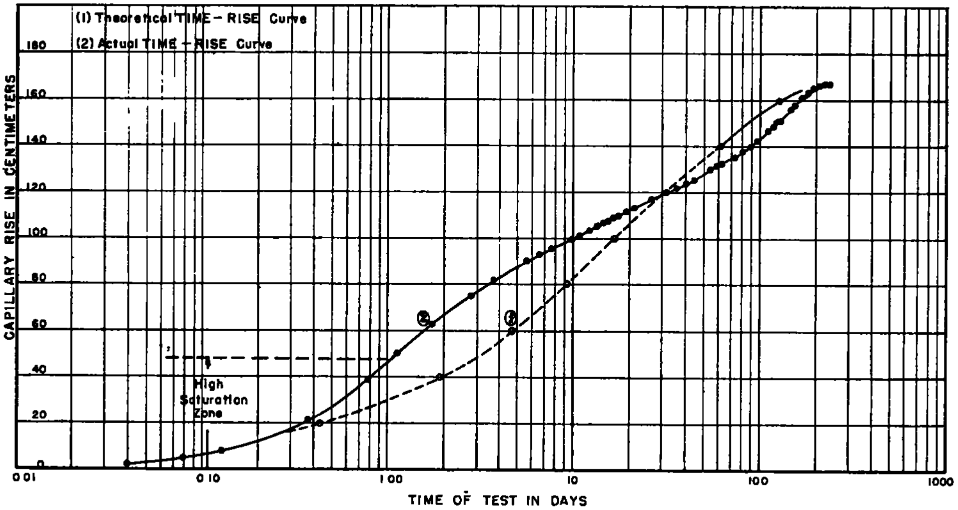


Figure 16. Capillary Rise-Time Curves—Class 7—Actual and Theoretical Rise

Possibility of better check with the theoretical formula solely in the zone of high saturation was investigated for the Class 6 sample by using the highly saturated height from Figure 9 as the value of h_c in the theoretical formula. Resulting theoretical curve is plotted on Figure 13 as that for the highly saturated zone only and does not agree at all with observed data except that for early values of time it is somewhat more parallel to the observed curve than is the theoretical curve for ultimate height of rise.

Neglecting consideration of deposition of air dissolved in the water, it appears that an equation to fit observed time-rise curves should be a combination of several functions rather than one as in the above formula. At start of rise in the long tube the influence of the larger voids is predominant; tension in the water causing the rise is supplied by fully developed menisci of radius, R_L, in these larger voids (such tension in the water being inversely proportional to the radius of the meniscus). Since tension in the water must be uniform at any cross section of the sample, menisci in the other voids have same radius, R_L, and thus are only partially developed. Rate of rise is then a function of $h_c = h'_{cL}$ (determined by the larger void size), $e = e'_t$ and $k = k'_t$ (both e'_t and k'_t being based on passage of water over the total void cross section of the sample). In latter stages the influence of the smaller voids becomes predominant; the rise is confined to the more constricted continuous void channels; and the sample cross section is only partially saturated. Tension in the water causing the rise is supplied by fully developed menisci of radius R_s in the smaller voids, and is much greater than at the start. Rate of rise is then a function of $h_c = h'_{cs}$ (determined by the smaller void size and much greater than h'_{cL}), $e = e'_s$ and $k = k'_s$ (both e'_s and k'_s being much smaller than at the start and based on passage of water through only the smaller void channels which represent only the saturated part of total void cross section). Thus for the usual soil having various sizes of voids, h_c, e and k are not constant for the period of rise, as necessarily assumed in deriving the formula given by Terzaghi.

Accordingly, it appears the above formula applies to an ideal soil where all voids are of equal size and the extent of agreement between this formula and observed data depends on how close the actual soil approaches such ideal soil. For the uniformly graded soils tested, Classes 4, 6 and 8, the agreement between the formula and observed data is fairly reasonable after correcting for a decrease in permeability due to entrapment of dissolved air (see Fig. 12, 13 and 14). Results with variably graded soils, Classes 5 and 7, are compared with curves from the formula on Figures 15 and 16. Agreement in shape of the curves is far less than for the uniformly graded soils apparently due to the much greater variation in void sizes to be expected in variably graded soils containing appreciable coarse aggregate. Because of this poor agreement no attempt has been made to match the curves at $\frac{h_c}{2}$ by correcting for changed permeability.

CONCLUSION

From the above reasoning the chances are not promising for developing a theoretical equation for the rate of rise; whence indirect permeability tests by vertical capillary rise methods are not apt to give other than a very crude approximation of the permeability. However the amount of rise is usually of most interest and it appears that this should be determined as the active capillary rise from longtime open tube tests. The much smaller height of rise by the capillarimeter method is not considered comparable to the case in nature. As further data becomes available it may well be possible to prepare plots similar to Figure 6 which will serve adequately for estimating the capillary rise from grain size and permeability test results. From present data it appears probable that an eventual plot for comparing results from different investigators should involve a family of curves based on such variables as height of rise, effective size, and Hazen's uniformity coefficient $\left(\frac{d_{60}}{d_{10}}\right)$ or based on height of rise, permeability and uniformity coefficient.

REFERENCES

1. Phillip Keene, "Underdrain Practice of the Connecticut Highway Department," *Proceedings*, Highway Research Board, Vol. 24, (1944)
2. Fahlquist and Kenerson, "Providence Soil

Classification," Discussion in *Proceedings*, ASCE Oct. 1939

3. Casagrande and Fadum, "Notes on Soil Testing for Engineering Purposes," Soil Mechanics Series No. 8, Harvard University
4. Highway Research Board Wartime Road Problems Bulletin No. 8
5. G. E. Bertram, "An Experimental Investigation of Protective Filters," Soil Mechanics Series No. 7, Harvard University
6. Raul Valle-Rodas, "Capillarity in Sands," *Proceedings*, Highway Research Board, Vol. 24, (1944)
7. K. v Terzaghi, "Soil Moisture," Physics of the Earth, Vol. 9, McGraw-Hill, (1942)
8. K. v Terzaghi, "Theoretical Soil Mechanics," page 303, John Wiley, (1943)

DISCUSSION

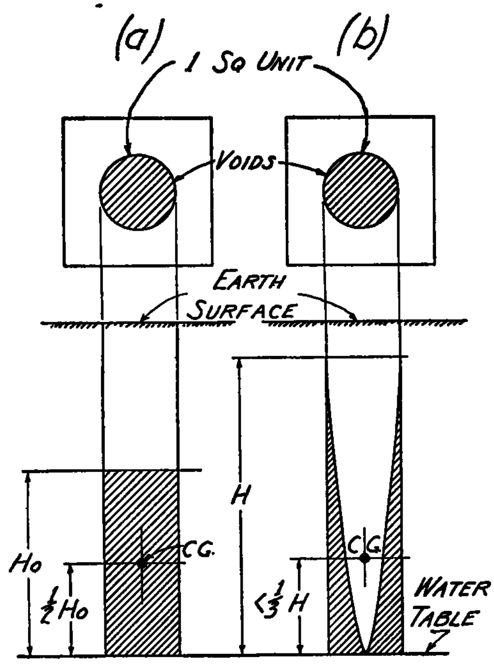


Figure A. Height of Capillary Rise—(a) from capillarimeters; (b) from tube tests

Prof. D. P. Krynine, *Yale University:* It seems to me that considerable differences in the height of capillary rise as determined from capillarimeters and from tube tests, could be explained as follows. In Figure A a vertical prism of soil of arbitrary cross-section (rectangular on the drawings) is shown. The sum of all voids of this prism is represented by a vertical cylinder (cross-hatched circle in plan, area 1 sq unit). It will be assumed that, under given circumstances, the prism in question possesses a capacity of producing a certain constant amount of work in lifting moisture from the water table. Figure A(a), left, shows the height H_o as measured by a capillarimeter, this height corresponding to complete saturation of the soil (100 percent degree of saturation). It may be stated approximately that the soil under consideration can produce the work of lifting a volume of moisture H_o cu units to a height of $\frac{1}{2} H_o$. In a test tube, however, the capillary moisture is redistributed along a larger height H (Fig. A(b), right) because in this case the degree of saturation is under 100 percent. If the lifted volume in both cases shown in Figure A is approximately the same, the centers of gravity of the lifted moisture are located at about the same elevation. The moisture distribution curve (Fig. A(b)) is generally concave; and if it were a straight line, the center of gravity of the lifted moisture would be located at the height of $\frac{1}{3} H$ above the water table. Hence to find the actual height, H, of capillary rise in a test tube as compared with the height H_o as measured in this particular case with a capillarimeter, it is necessary to consider Equation (1):

$$\tfrac{1}{2}H_0 = \tfrac{1}{3}H \quad . \quad . \quad . \qquad (1)$$

from which $H = \frac{3}{2} H_o$, or a difference of 50 percent. If the center of gravity of the lifted moisture is located at $\frac{1}{4} H$, then:

$$\tfrac{1}{2}H_0 = \tfrac{1}{4}H \quad \ldots\ldots \qquad (2)$$

i.e. in this case, the height of capillary rise in an experimental tube is double in comparison with that measured with a capillarimeter.