SOME EXPERIMENTS ON CAPILLARY FLOW OF MOISTURE THROUGH GRAVELS AND SILTS

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SYNOPSIS

Capillary movement of moisture in gravels and silts, and also in combined systems (silt-sand and silt-screenings) is described in this paper. The experiments were performed in large lucite tubes, 5⅝ in. and 3⅝ in. in diameter and 4 ft high. The shape of the time curves obtained by plotting the height of the visible moisture boundary against time was parabolic of variable order. By plotting the accumulated volume of moisture lifted by the soil against time, discharge curves for a part of the experiments were traced and their shape compared with that of the time curves. The moisture content along the height of an experimental tube generally decreased from the bottom towards the top, being, however, practically uniform in some particular cases. Attempts to understand the mechanics of capillary flow were made by interrupting the capillary process at different heights of capillary rise and measuring the corresponding moisture contents. It was concluded from the study of moisture distribution and from observations of condensation phenomena inside the tubes, that the moving capillary moisture is preceded and accompanied by water vapor. The conclusions formulated in this paper must be considered as specifically pertinent only to described conditions, and further research data along these lines are needed.

Three series of experiments on capillary flow of moisture in soils as described in this paper were made by the writer in the soils laboratory of Yale University, namely:

Item A. In 1942, capillary movement of moisture in gravels was studied for the Connecticut State Highway Department which at that time was it interested in capillary properties of gravels as material for subgrades and underdrains.

Item B. In 1945, capillary movement in adjacently placed materials such as silt and sand, or silt and screenings, was studied, also for the Connecticut State Highway Department, in order to clarify the interaction of soil materials in underdrains.

Item C. Finally, also in 1945, experiments were made on capillary movement through silts. The objective of these experiments was to approach as closely as practicable the conditions of capillary flow in cohesive soils since the majority of published data along these lines refer to sands only. Due to technical difficulties, however, the experiments in question were performed on slightly moist and not on wet silts as would be preferable.

PROCEDURE

The soil material was packed into lucite tubes 4 ft. long. There were two kinds of these tubes: wide tubes and narrow tubes, the inside diameters of these tubes being 5⅝ in. and 3⅝ in., respectively. The tubes were standing on metallic bases provided with holes (Fig. 1). The metallic bases were filled with clean, uniform ¼-in. gravel (average size). In the later experiments gravel was replaced by standard Ottawa sand (size of grains between 0.047 and 0.0006 in.). The gravel or sand was placed on, and covered with, filter paper. The thickness of the gravel or sand layer in question was 1 in. The material under test was placed on the filter paper on the top of this gravel or sand layer.

For filling the lucite tubes special cardboard tubes were built. The dimensions of the cardboard tube used for filling a wide lucite tube were 6½ in. in length and 3¼ in. in inside diameter, the latter dimension being smaller in the case of a narrow lucite tube. These cardboard tubes were provided with a round flap bottom. A simple system of strings kept this bottom closed when the cardboard tube was lowered into the lucite tube. At the required level the flap bottom was opened by manipulating the proper string. In this way the possibility of disaggregation of the experimental material and its separation into fractions of different size during the loading was substantially decreased. The material placed in the tube in portions was flattened and slightly compacted by using a long stick with a wooden disk at the end. To decrease the voids ratio, light blows of a hammer were applied to the outside surface of the lucite tubes. This procedure was not used, however, at the beginning of the experiments. The lucite tubes were filled to 3.6 ft. above the top of the gravel layer in the base, and this height decreased during the experiment. The final elevation of the top of the soil column above its base is marked on the drawings in all cases when the visible boundary of the capillary moisture reached that top. The average voids ratio of the material loaded into a tube was determined from the volume of the tube, the weight of the material loaded and the specific gravity of the particles. The latter was determined for gravels and trap screenings and assumed to be 2.65 for sands and silts.

The lucite tubes with the metallic bases at their tips were placed in 10- by 15-in. enamel trays about 2½ in. deep. The number of lucite tubes placed in one tray is indicated hereafter when describing individual experiments. The water level in the trays was that of the top of the gravel layers in the bases. In this way this top was the zero level of the rising capillary water. A constant water level in the trays was maintained automatically by using reversed flasks filled with water, these flasks being fixed on metallic stands (Fig. 2). When the water supply in a flask was nearly exhausted, the flask was weighed, refilled, and reweighed. In this way the discharge, or the weight of water lifted by the soil column during a certain time interval could be computed.

When water was applied to the soil column, bubbles of entrapped air, if any, were removed from the interior of the base (Fig. 1). This was done simply by using a thin rubber hose. For this purpose the openings A in the base (Fig. 1) should be wide enough.

To decrease the effects of evaporation, the top of a lucite tube was covered with a cardboard cover in which were numerous small slits. A small container with water was suspended between this cover and the top of the soil mass to create a rather saturated atmosphere.

The duration of the experiments is indicated hereafter in each particular case. During the course of an experiment observations of the visible moisture level were made, rather frequently at the beginning of an experiment and less frequently afterwards. Temperature records were taken at each visible moisture level reading. In the experiments of the last series (Item C, "Experiments with Silt") temperature, relative humidity of the air in the room, and, at the very end of the work, barometric pressure, were automatically recorded. The rate of evaporation from the enameled trays was determined by observing evaporation of water from special evaporation trays (described in more detail under Item C).

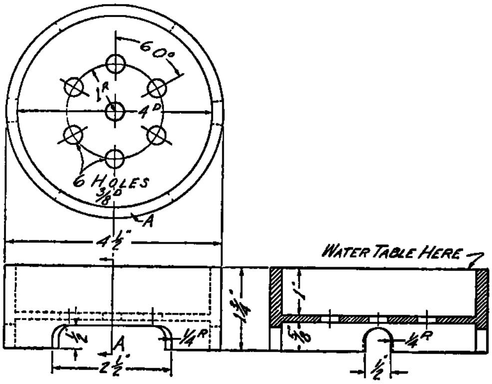

Figure 1. Metallic Base for Narrow Lucite Tube

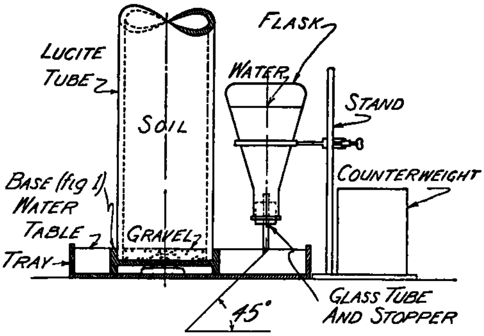

Figure 2. Reversed Flask to Maintain Constant Water Table

PLOTTING RESULTS

To determine the moisture content at different points of a lucite tube at the end of an experiment, the tube was placed horizontally on a table, the base of the tube was taken off, and the material was removed from the tube by portions, generally 0.4 ft. long, though in many cases much smaller lengths were used. The average moisture content of each portion was determined by drying the material to constant weight. In a general case, to construct the curve of capillary moisture distribution, a vertical line representing the tube was traced, and at the middle of each portion a horizontal ordinate equal to the average moisture content of that portion was plotted.

The heights of the visible level of capillary moisture, h (termed also "readings" hereafter), if plotted against the corresponding times, t, furnish curves which for the sake of brevity only, are termed "time-curves" hereafter. Time-curves may be expressed by Equation (1):

$$h^N = ct \quad \ldots\ldots\ldots (1)$$

where h is the visible height of capillary rise as above expressed, for instance, in ft., t, the time in days or hours; and c, a constant which has been assumed to be characteristic of a given material and depending, of course, on the measures in which the values of h and t are expressed. As to the value of N, it may or may not be constant. If it is constant, the curve expressed by Equation (1) is a parabola of the Nth order. The value of $N = 2$ corresponds to the common parabola. In many cases the time curve consists of parabolic segments of variable order.

MATERIALS USED

Six gravel samples were used, all from the State of Connecticut. Their provenance is: Sample No. 95086 from North Haven; samples Nos. 94856 and 94795 from Newington; sample No. 95057 from Weston; sample No. 95024 from Limerock Station and sample No. 95065 from Oxford. Since Connecticut gravels are products of glacial action and hence are mineralogically and petrographically very heterogeneous, no efforts were made to identify their mineral components. The results of the sieve analysis of the gravels are represented in Table 1. The portions of the size distribution curves of these gravels corresponding to the finer particles are shown diagrammatically in Figure 3.

The materials used in the experiments described under Items B and C of this paper are: (a) silt I and silt II, both from the North Meadows of the Connecticut River, Hartford, Conn.; (b) pink concrete sand from the same locality and (c) half-inch trap screenings. The size distribution curves for silts and sands are shown in Figure 4.

TABLE 1
SIEVE ANALYSES OF THE GRAVELS

Sample Number	95086	94856	94795	95057	95024	95065
Sieve	Material Passing Given Sieve					
	Percentage by Dry Weight					
5-in.			100.0	100.0		
3½-in.	100.0	100.0	96.0	94.3	100.0	100.0
1½-in.	91.8	86.2	78.1	69.3	73.3	61.4
¾-in.	47.3	36.2	46.3	31.8	37.7	37.3
No. 10	25.5	15.1	17.9	19.3	19.2	19.8
No. 40	8.7	3.7	2.6	4.9	8.5	6.1
No. 100	3.2	2.0	0.9	1.5	5.0	1.5
No 200	1.79	1.05	0.43	0.67	2.44	0.39
No. 325	0.14	0.12	0.18	0.17	0.55	0.14

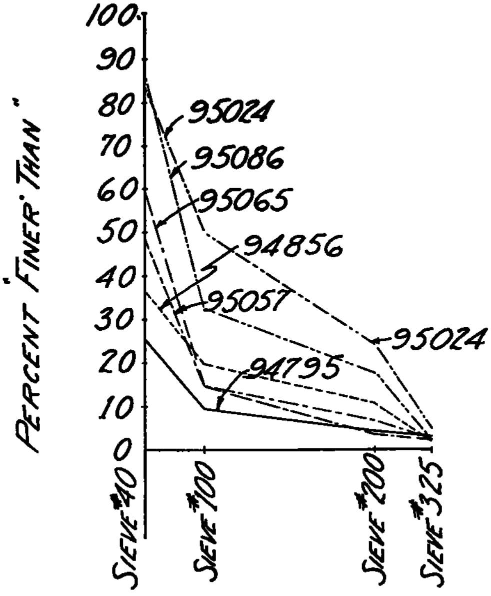

Figure 3. Size Distribution Curves of Gravel Fines Passing Sieve No. 40

The maximum height of capillary movement in both silts I and II is over 4 ft. Their consistency limits are:

	LL	*PL*	*PI*
Silt I	37	26	11
Silt II	28	22	6

The sand used in the experiments contained fine gravel, the latter being retained on sieve No. 10 (15.2 percent by dry weight). The fraction of the sand passing sieve No. 325 was 0.2 percent of the weight of the sample. Trap screenings of irregular shape were totally retained on sieve No. 4 (opening 0.187 in.). The specific gravity of the screenings washed with hot water was 3.03, the loss in weight in the washing being very close to 0.1 percent. The coat covering the screenings was fine basalt powder 84.6 percent of which passed through sieve No. 200 and 63.7 percent passed through sieve No. 325. In the experiments described hereafter the screenings were used unwashed.

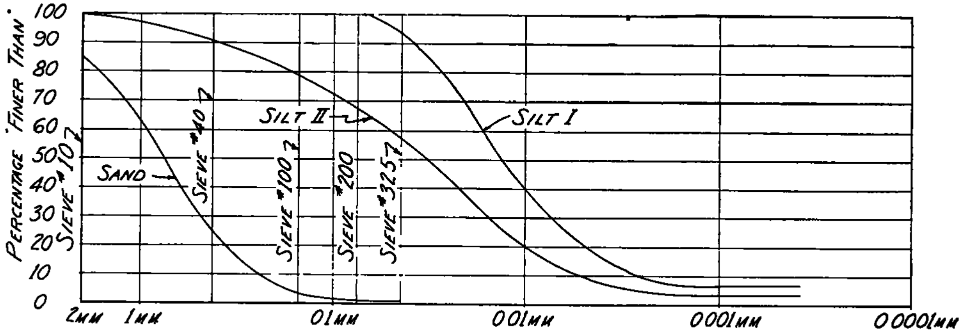

Figure 4. Size Distribution Curve for Sand and Silts

ITEM A.—EXPERIMENTS WITH GRAVELS

All lucite tubes used in the experiments with gravels were narrow tubes. The first three samples of Table 1 were tested between Feb 6 and Sept 11, 1942; the total duration of the test being 218 days. Samples 94856 and 94795 were placed together in one enameled tray, whereas sample 95086 was in another tray. During the time-interval mentioned, the water level in the tube with sample 95086 rose 3 ft, whereas in the tube with sample 94795, the level reached 1.8 ft only (Fig. 5). As to sample 94856 the visible moisture level in it was clearly distinguished up to May 1942. Afterwards moisture close to this level became foggy, and its level was difficult to establish. Apparently, the moisture at the level passed into the hygroscopic state. The day temperature in the laboratory during this experiment fluctuated between 72 and 79 F. The night temperature was considerably lower but was not recorded. No correction for temperature was introduced in Figure 5.

The remaining three samples (Table 1) were tested between Oct 17, 1942, and Mar 24, 1943 (duration of the test 158 days). Sample 95024 was tested in an individual enameled tray, the other two samples being placed together. The visible moisture rose in all samples to a level of 2.7 ft or a little higher (Fig. 6). The day temperature during this experiment was between 71 and 76 F. The night temperature was not recorded.

To make the time-curves in Figures 5 and 6 comparable the visible heights of capillary rise corresponding to 158 days should be measured in Figure 5 which furnishes heights of about 2.8 ft and 1.7 ft for samples 95086 and 94795, respectively. Again, at the right of both Figures 5 and 6 the moisture distribution curves are shown. To make any two of these curves comparable, the percentages should be multiplied by the ratio of the unit weights which, together with the voids ratios, are shown at the bottom of Figures 5 and 6 (at the right).

The time-curves of all gravels tested are approximately parabolas of the fourth order ($N = 4$). The time-curve of sample 95024 is close to a parabola of an even higher order (N between 4 and 5). The writer had the opportunity to examine the time-curves for other Connecticut gravels as studied by Mr. Philip Keene, of the Connecticut State Highway Department. These curves were also approximately parabolas of about the third and fourth order.

From the examination of Figures 5 and 6 and the results of the weighing of the gravel extracted from the tubes, the following statements may be formulated:

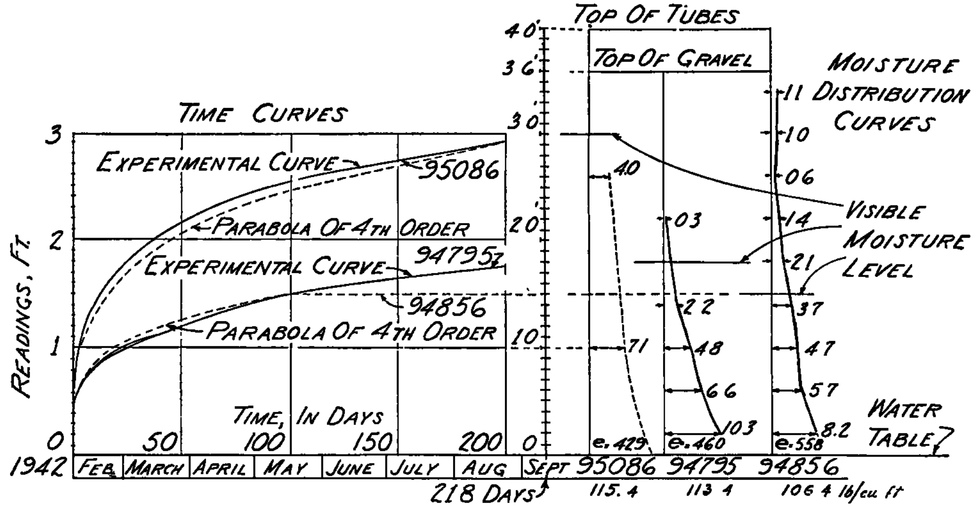

Figure 5. Capillary Rise in Gravels

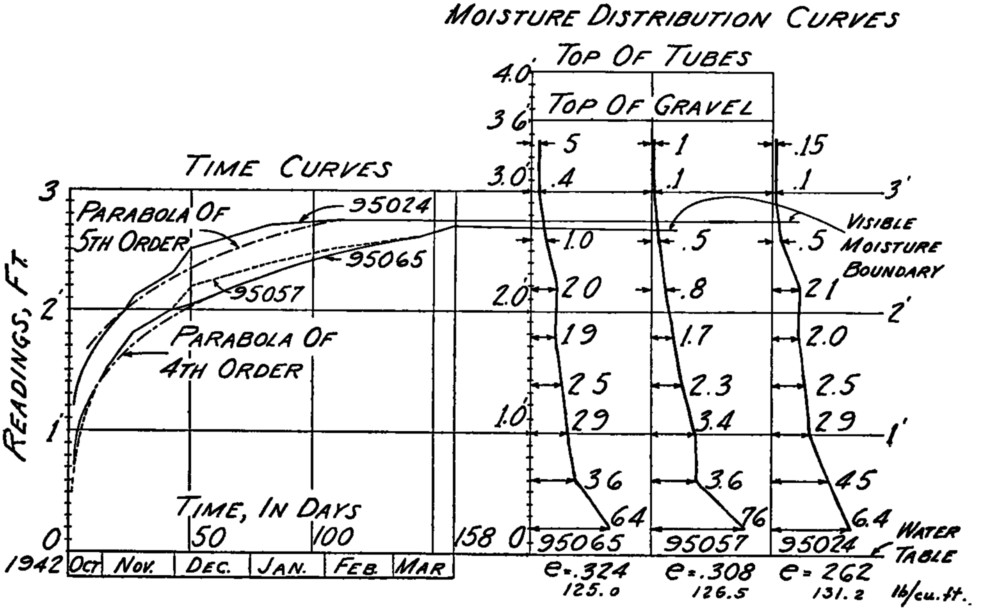

Figure 6. Capillary Rise in Gravels

1. In gravels with a considerable content of the fraction passing sieve No. 40 capillary moisture rises more quickly than in other gravels (example: samples 95086 and 95024).

2. Apparently the tighter the packing of a gravel (small value of the voids ratio, *E*), the less the total weight of the water lifted by the gravel from the water table. This

total weight under experimental conditions described was, for all gravels tested, roughly between 2 and 3 percent of the gravel by dry weight.

3. Loose packing of the gravel material apparently retards the capillary rise.

4. The moisture content decreases from the bottom towards the top of the gravel column. A few insignificant exceptions at the top of the gravel column were observed.

ITEM B.—EXPERIMENTS WITH ADJACENTLY PLACED MATERIALS

Using the home-made loading device previously described (under heading PROCEDURE) and a movable thin partition, a wide lucite tube was loaded with silt I and trap screenings, both materials being separated by a central vertical contact plane. To avoid dust, additional moisture was added to the silt material before loading to make its total moisture content three percent by dry weight. A similar test was made using silt I and sand. In both cases, the packing of the materials was rather loose, the voids ratios of silt I being 1.96 in both tubes. The voids ratio of the screenings was 1.02, and that of the sand 0.55.

The silt-screenings experiment started at 10:17 AM, Jan 22, 1945 and moisture reached the top in the night from Jan 25 to Jan 26. Two tracings were made by applying transparent paper to the outside surface of the lucite tube and the apparent moisture boundary curves in both silt and screenings were developed on a plane (Fig. 7). The solid line in Figure 7 corresponds approximately to noon, Jan 25, whereas the curve shown by alternate dashes and points corresponds approximately to noon, Jan 27. The moisture in the screenings followed closely that in the silt which advanced vertically very rapidly. It should be concluded that the screenings were extracting (sucking) moisture from the silt horizontally and at the bottom of the screenings column vertical capillary movement also took place. Moisture within the screenings body amounted to 0.32 lb only, or 3.8 percent of the weight of the moisture lifted by the soil (8.31 lb). In the experiment with silt I and sand the latter contained 1.19 lb of moisture from which 1.01 lb were concentrated in the lower third of the sand body and only 0.18 lb were extracted horizontally from the silt. This constitutes 2.2 percent of the moisture lifted by the silt in this case (8.12 lb). The moisture extracted from the silt by the sand was presumably in hygroscopic state and could not be seen with the naked eye.

Figure 8 represents moisture-distribution curves for the two experiments just described and for one additional experiment which was run for checking purposes using only silt I placed in a narrow tube. The general feature of the three curves is a striking uniformity of the moisture content through the height of the tubes, which is about 50 percent in the case of the first and the second (from the left) curves, whereas moisture contents in the third curve are slightly greater. There was a delay of about 74 hr in extracting the soil from the latter tube, the contact of the soil column with water being maintained during this whole time interval.

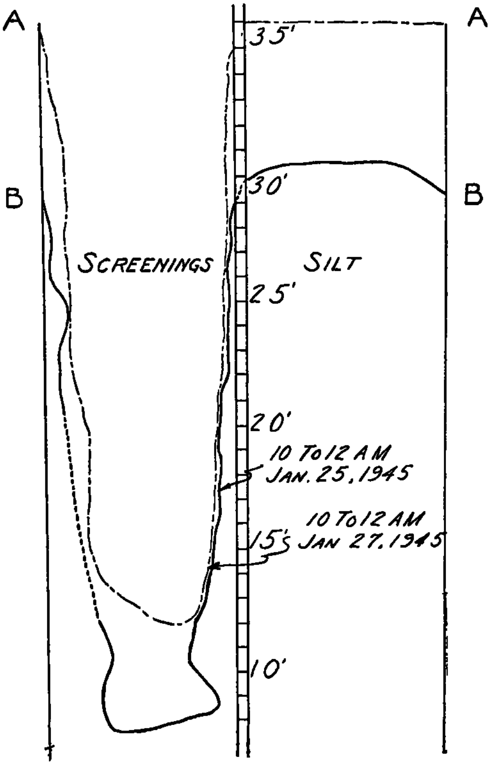

Figure 7. Apparent Moisture Boundary in Silt and Screenings

In the three cases shown in Figure 8 the degree of saturation did not reach 100 percent, i.e. not all pores were filled with moisture. The moisture content of a fully saturated soil, w, as expressed in fractions of a unit is:

$$w = \frac{e}{s} \quad \text{.................(2)}$$

where e is the voids ratio and s specific gravity of the grains. For the curve at the right, Figure 8, $e = 1.58$ and $s = 2.65$, hence the expected value of the moisture content in the case of full saturation would be about 60 percent, and more for other two curves. In reality, the moisture content in question did not reach these values (Fig. 8).

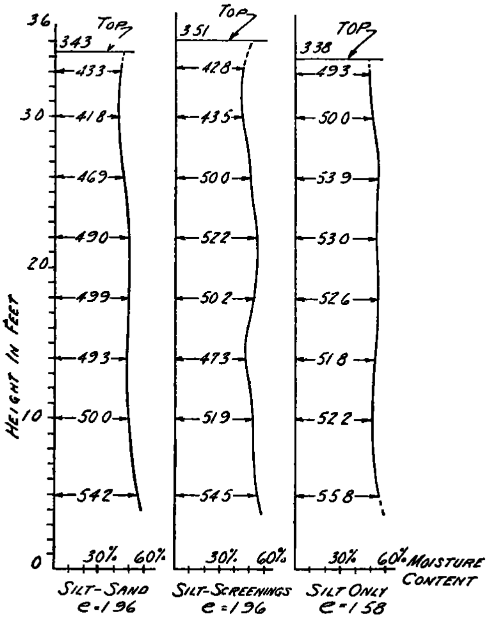

Figure 8. Moisture Distribution in Silt I

Attention should be called to a local decrease in moisture content close to the water table (not shown in Figure 8, but seen in Curve 1 and 4, Figure 10). The moisture content at the water table corresponds to a 100 percent degree of saturation as referred to the material below the water table (sand or gravel); and the voids ratio e_o of this material is smaller than the voids ratio e of the silt above the water table ($e_o < e$, Figure 9b).

ITEM C.—EXPERIMENTS WITH SILT

In these series of experiments silt II was used (Fig. 4). At each observation the following data were recorded: (a) time, (b) height of the visible boundary of the capillary moisture ("reading," in ft), (c) weight of a special evaporation tray, and (d) in a few instances, barometric pressure. Relative humidity and temperature were recorded continually through the whole experiment by an automatic recorder located at the level of the base of the soil column at a horizontal distance of about 3 ft from it. Since the loss of water from the inverted flasks (Fig. 2) equals the sum of the weight of the capillary moisture lifted by the soil and that of the water evaporated from the enameled tray in which the tubes are standing during the experiment (neglecting evapora-

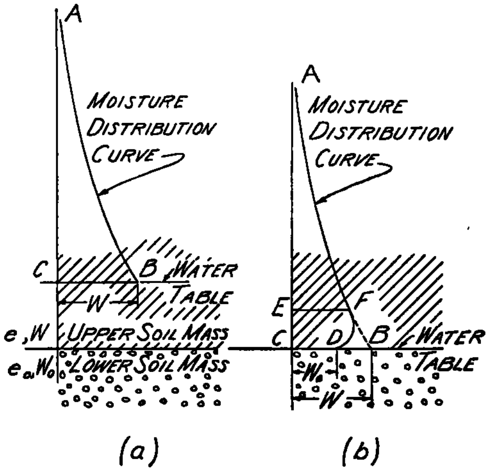

Figure 9. Idealized Moisture Distribution of Capillary Rise

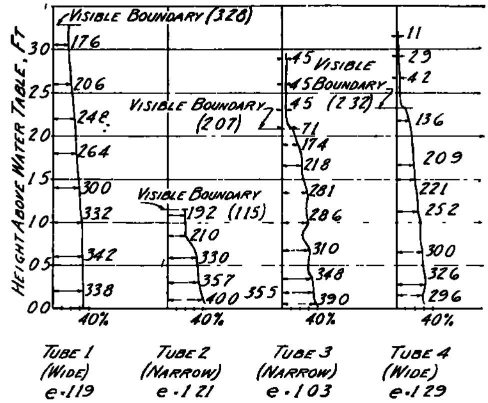

Figure 10. Moisture Distribution in Silt II

tion from the top of the experimental soil column), it was necessary to introduce correction for evaporation. Evaporation trays were 8- by 12-in. Pyrex trays about 2 in. deep, filled with water. It was assumed that the ratio of the evaporation rates from an enameled tray and from an evaporation tray equals the ratio of their areas (1.56:1). According to some theoretical considerations,[1] evaporation is proportional to the diameter (or other lineal dimension) of the evaporating surface and not to its area. The ratio of the lengths of the two trays is 1.25:1, so that the correction for evaporation computed under this other assumption would be somewhat smaller.

The accumulated amount of moisture adsorbed by the soil (i.e. loss of water from the flasks, Figure 2, corrected for evaporation) is termed "discharge" in Figures 11, 12, and 13. It has been noticed that the shape of a discharge curve may be approximately expressed by a parabolic curve. In each of the cases represented in Figures 11, 12, and 13, the vertical scale for the discharge curve is constant, whereas the vertical scale for the time-curve is variable, and chosen in such a way as to make the two curves superpose.

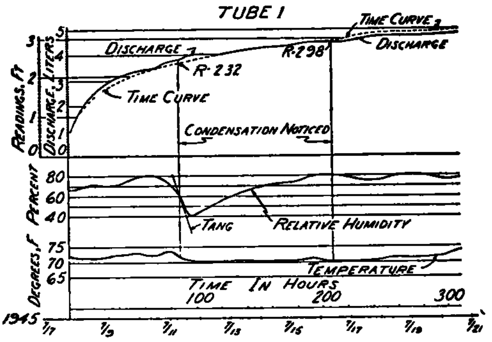

Figure 11. Discharge Curve, Tube 1 of Figure 10

The following experiments were made using silt II: (a) Moisture was allowed to reach the top of the silt column (tube 1, Fig. 10); (b) the capillary rise was discontinued before moisture had reached the top of the silt column (tubes 2, 3, and 4, Fig. 10). The corresponding heights of the visible boundary of the capillary moisture (readings) are shown on the drawings (Fig. 10). In the case of tubes 3 and 4, Figure 10, samples above the visible boundary of the capillary moisture were taken, and moisture contents determined. It was concluded that the flow of capillary water was preceded by the flow of water vapor which, upon being attracted by soil particles, forms moisture films on them. This "hygroscopic" moisture content in tubes 3 and 4, Figure 10, in one case was constant and in the other decreased towards the top of the soil column.

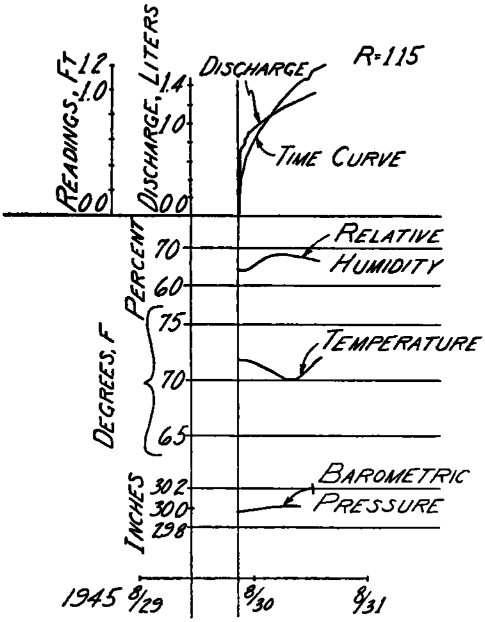

Figure 12. Discharge Curve, Tube 2 of Figure 10

The analysis of the time-curves of tubes 1, 3, and 4, Figure 10, was done in the following way. The ordinates h_1, h_2, $h_3 \ldots$ of a time-curve corresponding to some time-moments, such as $t_1 = 10$; $t_2 = 20$; $t_3 = 30$ hr . . . were measured and for each of these time-moments the values of the ratios $\frac{h_2}{t}$; $\frac{h_3}{t}$; $\frac{h_4}{t}$; $\frac{h_5}{t}$ computed. From an inspection of the results an average value of the param-

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[1] W. J. Humphreys, "Physics of the Air," McGraw-Hill Book Company, Inc., New York, page 252, (1940)

eter c for silt II was estimated at 0.1 (for feet and hours). Using Equation (1), it was found that the value of the parameter N varies; for tube 1, Figure 10, from 2 to 3; and for the other two tubes mentioned above, from 3 to 4. Both tubes 1 and 4 are wide and filled with the same material (silt II), hence the results obtained using them are comparable. The value of the voids ratio is 1.19 and 1.29 for tubes 1 and 4, respectively. Inspection of the time-curves shows that the rate of the capillary rise in tube 1 was larger than in tube 4. Hence, it may be concluded that looser packing in tube 4 retarded the flow, the same as in the case of gravels.

the visible boundary of the capillary moisture were observed again, however.

In tube 1, Figures 10 and 11, condensation was observed at 9:15 AM, Jul 11, 1945, the visible boundary of the capillary moisture standing then at the reading 2.32 ft (Fig. 11). In Figures 11, 12, and 13 the symbol "R" means "reading". Condensation at the western side of the tube facing the windows of the laboratory was more intense than at the eastern side. From reading 1.83 ft down to reading 0.3 ft the western side of the tube was covered by silver white, fine condensation moisture of variable intensity. At the eastern side, light, rather foggy, condensation was observed between readings 1.75 ft and 0.6 ft. Condensation in this case took place when there was a slight drop in temperature and a sudden, considerable drop in relative humidity (from about 80 percent to about 40 percent). The steepest tangent to the relative humidity curve corresponds to the time-moment when condensation was noticed (Fig. 11). Afterwards condensation moisture started to disappear without change in temperature (Fig. 11). For instance, on Jul 15 there was no trace of condensation at the eastern side of the tube.

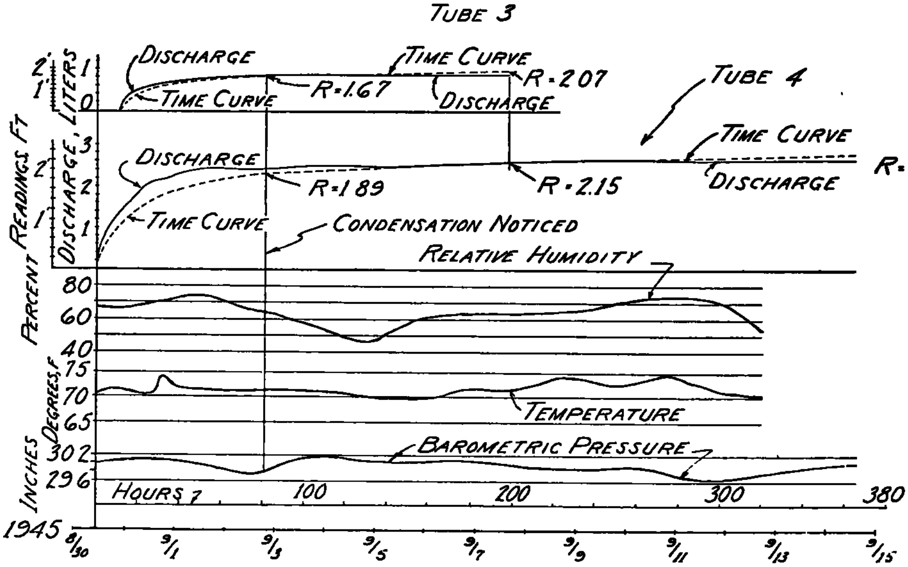

Figure 13. Discharge Curves, Tubes 3 and 4, Figure 10

CONDENSATION PHENOMENA

In the experiments described under Items A and B performed in winter, condensation moisture was observed at the inside surface of the lucite tube. This phenomenon was ascribed to the considerable difference between day and night temperatures in the laboratory. It was decided therefore to eliminate the influence of the temperature and to carry on the experiments described under Item C during the summer or early fall when the temperature of the laboratory is equable, varying from 70 F to 72 F, and rarely reaching 75 F if the windows are wide open in hot weather. Condensation phenomena below

In the morning of Jul 16, another instance of condensation occurred (the reading being

2.98). This time it coincided with a drop in relative humidity only, the temperature being constant before and after the condensation (Fig. 11). All moisture condensed at the western side of the tube only, its upper limit being at reading 2.50; a part of it remained until the end of the experiment (Jul 21).

Tubes 3 and 4, Figures 10 and 13, were together in the same enameled tray, and at about 7:00 PM on Sept 2, 1945, when the relative humidity was dropping but the temperature was constant, condensation moisture appeared in both tubes. The readings were 1.89 and 1.67 in tubes 3 and 4, respectively; and the upper limit of condensation in both tubes was about reading 1.00. In this connection no condensation moisture was observed either below reading 0.4 ft nor at the eastern side of the tube. On Sept 4, when the relative humidity was still decreasing, condensation moisture looked like coarse water drops; it persisted until the end of the experiment (Sept 14). No effort was made to connect the barometric pressure to the capillary rise in general and to condensation phenomena in particular.

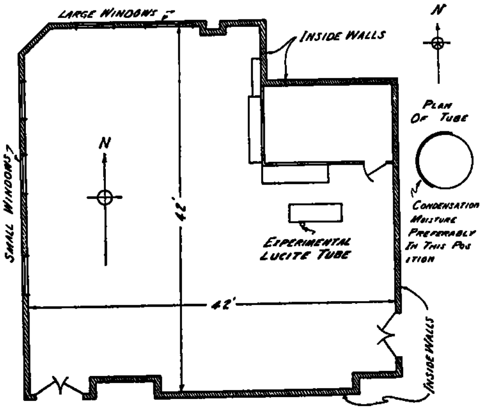

Figure 14. Plan of the Experimental Room

Condensation phenomena observed suggest the following: (1) Condensation below the visible boundary of the capillary moisture means that the water vapor not only precedes the moving fluid capillary moisture, as shown above, but also accompanies it, except perhaps at the very bottom of the experimental tube (0.3 or 0.4 ft) where no condensation was observed; (2) Besides a decrease in temperature, condensation in a confined earth mass (as in an experimental tube) may be due to a rather sudden drop in the relative humidity of the surrounding atmosphere, as occurred under the laboratory conditions described.

Figure 14 shows the plan of the experimental room accompanied by an enlarged plan of the experimental tube (at the right) showing the preferred (and in some occasions exclusive) position of the condensation moisture.

CONCLUSIONS

Experiments made by the writer do not furnish sufficient statistical material to formulate categoric conclusions. Hence the conclusions presented here should be considered as tentative and pertaining only to described conditions. These conclusions are:

1. The time-curves obtained by plotting the visible height of capillary rise in gravels and silts against time are formed of segments of parabolas of orders higher than the second.
2. Tight packing of a gravel decreases the total amount of capillary water lifted by a column of gravel of a given height.
3. Loose packing of gravels and silts retards the capillary rise.
4. In the case of both gravels and silts with a relatively limited percentage of fine particles the moisture content of the material in the experimental tube of the size and shape used in these experiments decreases from the bottom toward the top.
5. In the case of silts with a considerable percentage of fine particles the moisture content is practically uniform along the height of an experimental tube of the size and shape used in these experiments, the degree of saturation being below 100 percent, however.
6. Liquid moisture moving through a silt mass in a capillary way is preceded and accompanied by water vapor. Moisture films are being formed on soil particles above the visible boundary of the liquid phase.
7. Additional careful investigations are needed before accepting or rejecting the possibility of condensation in a confined soil mass as being caused by a decrease of the relative humidity of the surrounding atmosphere at a constant temperature.

ACKNOWLEDGMENT

The writer wishes to express his sincere thanks to Professor H. F. Winterkorn of Princeton University for his constructive criticism of the original draft of this paper.