striking similarity to a soil structure developed by Dr. Leo Casagrande in some of his experiments on the electrical treatment of clay soils (L. Casagrande, 1947) This coincidence is naturally to be followed up in the hope that it may lead to significant findings. It serves to confirm the impression, induced by detailed consideration of the test results so far summarised, that the mode of deposition of the soils in Steep Rock Lake is responsible for their unusual structure and high moisture contents.

Throughout all exposures of the soil so far examined, varying of the soil is very clearly demonstrated. So remarkable is this varving that Dr. Ernst Antevs, renowned expert on varves, spent some weeks at the Mine in 1946 and made a complete study of the varves, detecting five distinct series; his report will be published in 1948. The authors have followed up the work of Dr. Antevs by starting a detailed study of the soil types in individual varves. This work has only just been started but the results are already interesting (Bartley and Legget, 1947). Little difference is found between the grading curves for the particles in the light and dark varves, some difference is noted in the respective Atterberg Limits, and appreciable differences in the relative moisture contents of the several varves. Apparently the principal difference is one of soil structure and not soil composition. It is somewhat difficult to reconcile this with the generally accepted theory of alternating winter and summer deposits.

Photographs of particles from some of the soils described, taken with the aid of an electron microscope (through the courtesy of Dr. E.F. Burton and members of the staff of the Department of Physics, University of Toronto) fail to disclose any of the typical elongated particle shapes of the true clay minerals. This was to be expected since all the evidence presented suggests that the soils described consist of "rock flour" i.e. granular particles of relatively fresh rock minerals, despite their small size. Deposition of these soils, with so high a colloid content, must have been related to the varying electrolytic property of the water in which they were suspended, and this might have given rise to the thixotropic condition exhibited by the Steep Rock soils. Much work has yet to be done before a full understanding of the true character of these soils of northern Canada is reached, but it is hoped that this note of progress will be of interest to the International Conference if only for comparison with similar soils found in other countries.

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ANALYSIS OF THE LATEST AMERICAN TESTS ON SOIL CAPILLARITY

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INTRODUCTION.

In the past five years various laboratory tests on soil capillarity have been made in the United States using both vertical open tubes of various diameters filled with dry or practically dry soil powder and capillarimeters. A comparative analysis of the results of these investigations is made in this paper. For comparison purposes some capillary tests in glass tubes and in fibrous materials are also referred to.

1. CLASSIFICATION OF TESTS.

The tests analyzed in this paper have been made:

(A) by the physicists of the Bell Telephone Laboratories 1);
(B) by the physicists of the Louisiana State University 2);
(C) at Princeton University 3), using both vertical open tubes with soil and capillarimeters;
(D) in the Connecticut State Higaway Department 4), using vertical open tubes;
(E) by the U.S. Army Engineers .5), using both vertical open tubes and capillarimeters;
(F) at Yale University 6) using vertical open tubes.

Hereafter the tests mentioned above are identified as tests (A), (B), (C).......

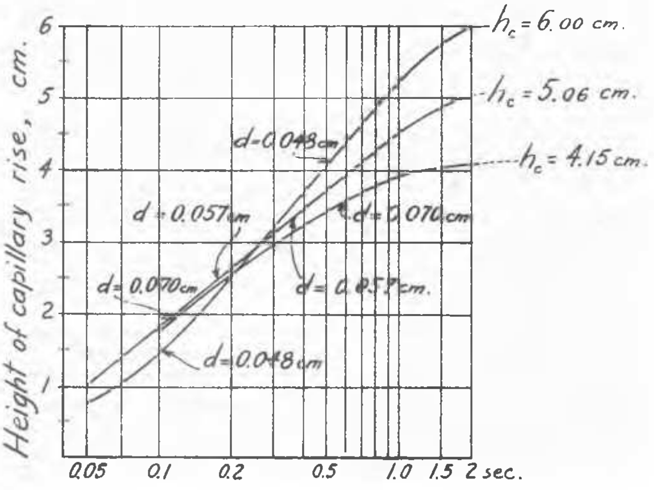
2. TESTS (A) AND (B).

(A) Strips of filter paper about 1 cm wide and about 20 cm long were suspended vertically with their lower ends dipping into a liquid. All measures to prevent evaporation were taken. The wetted portion was clearly demarcated from the unwetted by an even horizontal line. The demarcation line for this and other cases of capillary rise, is termed "wetted line," hereafter. Plotting the heights, h, of the wetted line above the water table against corresponding time t, "time-curves" were obtained. A graphical differentiation of a time-curve furnished Equation (1) corroborated by theoretical considerations. 1)

$$\frac{dh}{dt} = \frac{a}{h} - b \qquad (1)$$

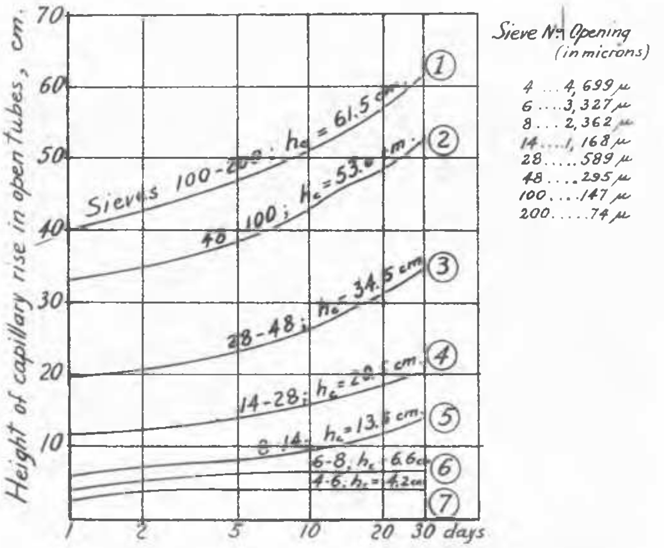
where a and b are parameters depending on the distribution of pore sizes in the medium and the viscosity of the liquid used. For six organic liquids the value of the parameter b proved to be very small which means that the ratio $\frac{h^2}{t}$ was practically constant as is the case of capillary movement in soil placed in horizontal tubes.

(B) The diameter d of glass tubes used in tests (B) is shown in Fig. 1 that represents time curves of capillary rise of water in glass tubes plotted on semi-logarithmic scale. The position of the wetted line at different time moments was recorded photographically 2). Stroboscopic light was used in the illumination of the tube, the time-intervals being of 1/10 and 1/20 sec. The rate of rise of water (at 25° C) increased as the diameter of the tube decreased (Fig. 1). In the same series of tests ethyl alcohol and glycol were also used for experiments. The maximum capillary rise h_c of these liquids in glass tubes of equal diameter is smaller than that of water, but both density and viscosity of glycol (but not of ethyl alcohol) are larger than in the case of water. The behavior of ethyl alcohol was similar to that of water, but the rate of rise of glycol (at 20.2° C) was much smaller 2). Time curves, Fig. 1, and all other time curves described hereafter, if plotted on simple arithmetic scale, are similar to parabolas of some higher order.



Tests (B): Time curves for water rising in glass tubes

FIG. 1



Tests (C): Time curves in open tubes with sand

FIG. 2

3. TESTS (C).

Clean sand from Morrisville, Pennsylvania 3) was separated into seven groups using sieves (Fig. 2). Figures accompanying the time curves in Fig. 2 such as 100-200, mean that all grains of a given fraction pass sieve No. 100, but are retained on sieve No. 200. Evidently sand fractions in tests (C) were very uniform.

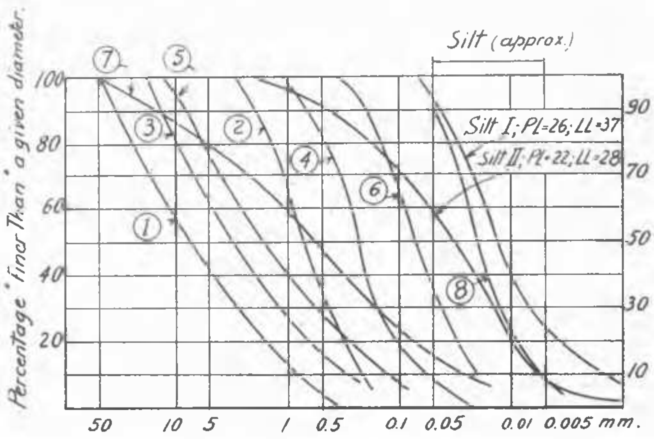
Symbol h_c as in Fig. 2 is used in this paper to designate the maximum capillary rise in a vertical open tube.

4. TESTS (E).

Lucite tubes of 5.08 and 10.16 cm in diameter were filled with dry soil powder tightly packed 5). The bottoms of the tubes were closed with a perforated brass plate, screen and cloth and rested on supports in a pan of water to an approximate depth of 5 cm. The typical size-distribution curves are shown in Fig. 3 (Classes 1-8). Other characteristics are in the following table 5).

Class	Specific gravity	Effective size d_{10} in mm	Average voids ratio e	Dry density $\frac{tons}{m^3}$	Maximum Capillary rise h_c in cm	Permeability $\frac{cm}{sec}$ k x 10^4
1	2.70	0.82	0.27	2.11	5.4	1100
2	2.65	0.20	0.45	1.82	28.4	160
3	2.70	0.30	0.29	2.10	19.5	71
4	2.70	0.06	0.45	1.87	106.0	4.6
5	2.69	0.11	0.27	2.11	82.0	1.1
6	2.75	0.02	0.66	1.64	239.6	0.62
7	2.77	0.03	0.36	2.06	165.5	0.096
8	2.76	0.006	0.93	1.43	359.2 x)	0.14

x) unfinished

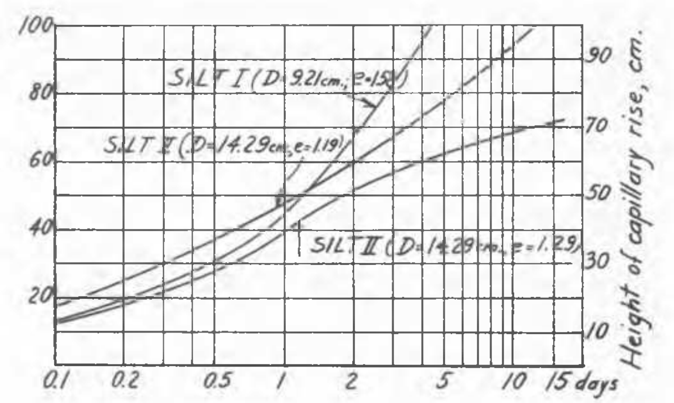


Tests (E) and (F): Size distribution curves

FIG.3

5. TESTS (F) AND (D).

(F) Lucite tubes 9.21 cm and 14.29 cm in diameter, 1.22 m long were used 6). The materials tested were gravels and silts. The size-distribution curves of two silts, I and II, and their consistency limits are shown in Fig. 3. Some time curves of these two silts are shown in Fig. 4 in which (and in Fig. 8) symbols D and e mean the diameter of the experimental tube (in cm) and the voids ratio, respectively. The specific gravity of grains of both silts is about 2.65. In testing silts systematic observations of temperature and relative humidity were made.



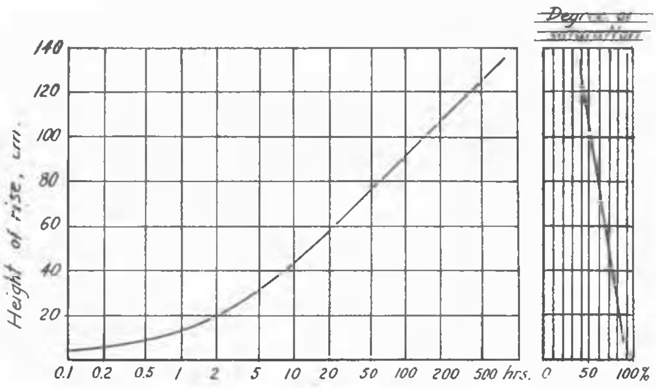
Tests (F): Time curves in open tubes with silt

FIG.4

(D) Fig. 5 represents a typical time curve of a "silty sand" of the same provenance as Silt II, tests (F), as above. Tests (D) were made in long open tubes to reach the maximum capillary rise h_c that for the given material is over 300 cm 4).

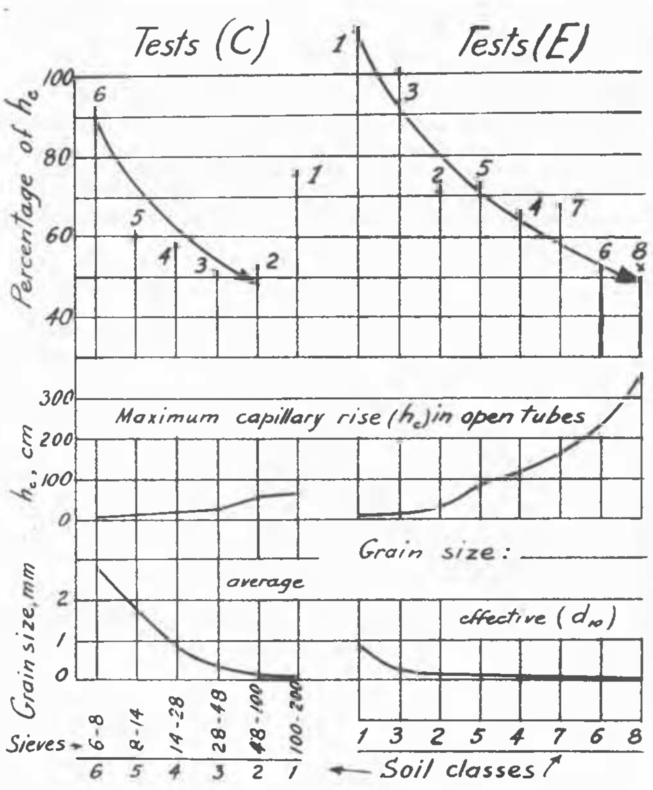
6. MAXIMUM CAPILLARY RISE h_c IN OPEN TUBES.

In Fig. 6 the soils classes of tests (C) and (E) are arranged in the descending order of soil grains. In the case of sand fractions (tests (C)) this is the average of the opening of the two sieves between which a given fraction is enclosed. In the case of soil classes of tests (E) this is the effective size d_{10}, i.e., the maximum diameter of the smallest 10 per cent by weight (Fig. 3). In



Tests (D): Time curve for a typical sand in open tube

FIG.5



Capillarimeters vis. open tubes

FIG.6

both tests (C) and (E), the smaller the grain size, the larger is the maximum capillary rise h_c.

7. CAPILLARIMETERS VIS. OPEN TUBES.

At the top of Fig. 6 the values of the maximum capillary rise in open tubes, h_c; for different soil classes of tests (C) and (E), are shown as 100 per cent ordinates. The corresponding heights of capillary rise as measured by capillarimeters are expressed in per cent of h_c and shown in Fig. 6 as vertical ordinates with small crosses at the top. Capillarimeters used were similar to the original type 7) as adopted by the Public Roads Administration 8) and U.S. Army Engineers 5). As the grain size decreases and the corresponding value of h_c increases, capillarimeter's readings deviate more and more from the value of h_c until for some fine soils only about a half of the value of h_c is furnished by the capillarimeter. This general decreasing tendency is shown by curved arrows at the top of Fig. 6. An exception is the finest sand fraction in tests (C) passing through sieve No. 100 and retained on sieve No. 200, and to a certain extent next fraction (sieves 48-100). Generally, porosity of uniform fine sands even in dense state is somewhat larger than that of medium or coarse sands. This is probably due to some change in pore geometry and consequent increase in retentive capacity during drainage. Hence the apparent anomaly observed. No such anomaly was recorded in tests (E) where more graded soils were used (Fig.6).

8. RATE OF RISE.

The theoretical formula for the time of rise t to a height z as based on the assumption of complete saturation of the earth material below the wetted line is: 9)

$$t = \frac{e\,h_c}{(1+e)\,k}\left[\log\frac{h_c}{h_c - z} - \frac{z}{h_c}\right] \qquad (2)$$

Placing:

$$z = m h_c \quad \text{and} \quad \frac{e\,h_c}{(1+e)\,k} = 1$$

the "rise function" t may be obtained:

$$t = -\left[\log(1-m) + m\right] \qquad (3)$$

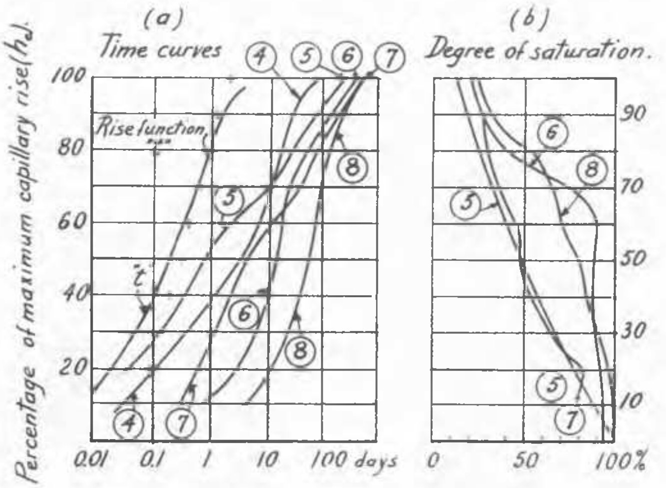
The term "rise function" is introduced here for the sake of brevity only.

If plotted on a semilogarithmic scale (Fig. 7a) the "rise function" resembles the curves in Fig. 1, for capillary rise in glass tubes except the case of m = 1, when its value becomes infinite. Small crosses next to the graph of the rise function t in Fig. 7a are points of the graph Fig. 1 for d = 0.048 cm. If soils really behave as bundles of capillary tubes as often assumed, their times curves in Fig. 7a should be horizontally equidistant from the graph of the "rise function" t. Time curves of tests (E) do not satisfy this requirement, however, though their general shape is roughly similar to the graph of the rise function, t. As compared with theory, classes 5 and 7, tests (E), decelerate their movement toward the top of the experimental tube whereas classes 6 and 8 slightly accelerate it. Besides, the horizontal distance between the graph of the rise function t and the time - curves of various classes differs considerably (in some instances 20 times) from that computed using formula (2).

In tests (C) it has been noticed that the maximum rate of rise during the first day of the tests corresponded to the medium sand passing sieve No. 14 and retained on sieve No. 28 (average diameter about 0.88 mm). It was generally observed in these tests that "finer grained sands have higher rates of capillarity than coarse grained ones."

9. DEGREE OF SATURATION AND MOISTURE CONTENT.

Fig. 7(b) shows the degree of saturation of the soil classes as in Fig. 7(a). Again two groups of soils should be distinguished (a) that formed by Classes 5 and 7 with gradual decrease of the degree of saturation in the upward direction and (b) that formed by Classes 6 and 8 in which the degree of saturation is practically constant or decreases slightly up to a certain height (0.6 h_c to 0.8 h_c) and afterwards decreases rapidly. Figs. 5 and 8 also reveal two analogous groups in tests (F) and (D): to group (a) as above belong Silt II, Fig. 8 and silty sand, Fig. 5 whereas Silt I (Fig. 8) belongs to group (b). Silts of group (a) are coarser than silts of group (b).



Tests (E): (a) "Rise function" and time-curves in open tubes; (b) Degree of saturation

FIG.7

10. CONDENSATION PHENOMENA.

In tests (F) on silts condensation at the inside surface of the experimental tubes was observed both when the temperature outside the tube was dropping and when relative humidity of the experimental room was dropping, even without change in temperature. No condensation was observed: (a) above the wetted line; (b) at a certain vertical distance below the wetted line; and (c) at the bottom of the tube. (Example: wetted line at 71 cm, upper limit of condensation at 56 cm, lower limit of condensation at about 9 cm, all these heights measured from the water table). Above the wetted line there was hygroscopic moisture of a few per cent, presumably in the form of films.

11. CASE OF WATER TABLE AT THE BOUNDARY OF SAND AND SILT.

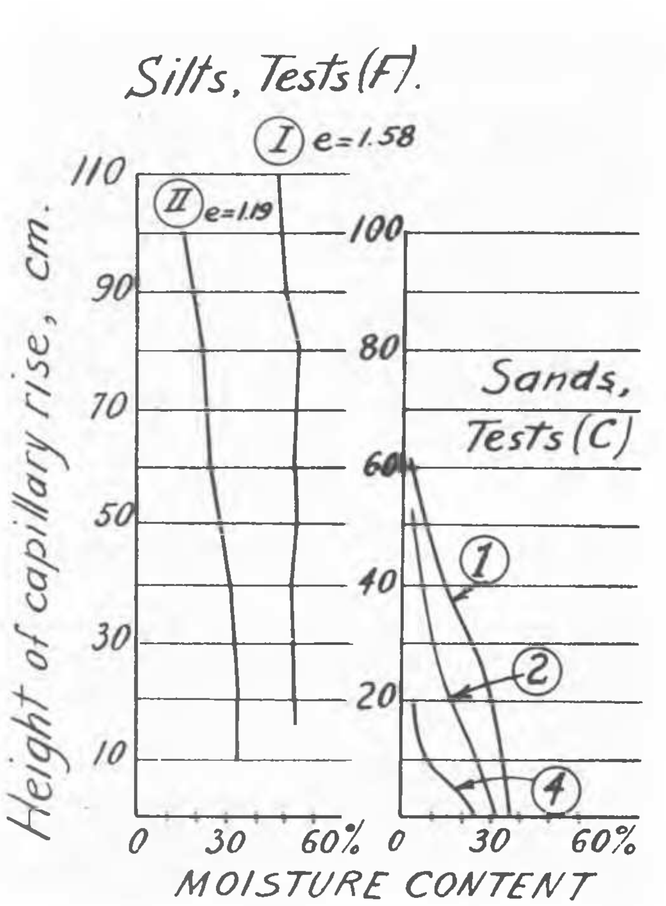
Capillary moisture fills all the pores of a soil at the level of the water table. If silt is underlain by sand and the water level is at the boundary of the two soils, the moisture content of the silt at the water table is controlled by the porosity of the sand. It increases on a certain distance in the upward direction, after which starts to decrease as shown by Tests (E).

CONCLUSIONS.

No laboratory tests on capillarity in wet soils or in clays were made. The conclusions presented hereafter should be considered as pertaining to described materials and conditions.

a) Time curves in fibrous materials (such as filter paper) are essentially of the same shape as in some cases of soils in open tubes (Sec. 1 of this paper).

b) Time curves of capillary rise of liquids in glass tubes are essentially of the same shape as the graph of the "rise function" t, in the theoretical formula of the time of rise in soils (Secs. 1 and 8);



Moisture contents: left side, silt tests (F); right side, sands tests (C)

FIG.8

c) The rate of capillary rise in glass tubes of liquids of larger density and viscosity than ordinary water is smaller than that of ordinary water (Sec. 1). In ordinary water the opposite is true (Sec. 1). By analogy, capillary water in sands approaches ordinary water and rises quickly in fine capillarities, whereas capillary water in fine grained soils is more dense and viscous, due to attraction, and hence moves slowly in fine capillaries. This analogy requires further research, however,

d) The factor preceding the "rise function", t, in the theoretical formula of the time of rise (2), is not constant for a given soil. Among soil characteristics on which the value of this factor depends, the particle size or a function thereof should be included.

e) Materials known as "silt," i.e., soils possessing mostly particles between 0.05 mm and 0.005 mm in size (approximate limits), should be subdivided into two groups, according to the percentage of coarser admixtures. The soils with a small (or none) percentage of coarser admixtures and hence with a smaller coefficient of uniformity, possess higher values of the maximum capillary rise hc and rather uniform moisture content (or degree of saturation) in the lower half of the capillary column (Secs. 6 and 9).

f) The maximum capillary rise in open tubes h_c primarily depends on the size of the soil particles and increases as the size of particles decreases (Sec. 6). Particularly in sands the height h_c and the moisture content above the water table increase as the average sand-grain size decreases (Fig. 8);

g) Capillarimeters as applied to the soils tested, did not prove satisfactory (Sec.7)

h) Information on the state of capillary moisture in open tubes is available for silts only. In this case water vapor precedes and accompanies the moving liquid phase (Sec. 10).

i) The degree of saturation in all tests was below 100 per cent. It is possible, however, that at the very bottom of the experimental tube where in the case of silts no condensation was observed (Sec. 10), the pores are completely filled with water.

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