ON CAPILLARY FORCES IN NATURAL SOILS

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Introduction

IT has been well known that when a soil is flooded there is a plane air-water boundary which has a zero pressure deficiency. As water is removed, menisci are formed at the surface and the plane air-water surface is converted into air-water-soil boundary. This stage is marked at the end of the capillary stage and beginning of the funicular stage. Considerable work has been done on the pressure deficiency at this transition stage on materials having uniform size such as " glistening dew ". " Glistening dew " consists of glass beads of uniform size and obtainable in various grades. So far as experiments on this material are concerned, theory and experiment seem to indicate that a soil aggregate might be considered to consist of a bundle of capillary tubes and the pressure deficiency at the transition stage might be represented by the equation $p = \mathrm{KT}/2\,r$. In this equation, p is pressure deficiency, K is capillary coefficient, T is surface tension of the liquid and r is the radius of the particles of soil. While this may be true in the case of ideal, uniform spheres, it is of practical importance to investigate how far conclusions derived from studies of uniform spheres can be applied to natural soil. Again, the method usually employed to determine the pressure deficiency is to place a small column of soil of 3 to 4 cm. in height in a Buckner funnel fitted with a filter-paper and to submit this to a negative pressure. This method precludes the possibility of experimenting with different lengths of columns of soil. The effect of capillarity and negative pressure* on columns of soil which are longer than what is known as the capillary height of soil is of especial importance in irrigation problems. In the experiments to be described in the present paper, the technique has been so arranged that different heights of the column of soil can be examined and the negative pressures determined.

* The term " pressure deficiency " has been used by previous workers for this phenomenon. This differs from the pressure deficiency obtained in porous pot experiments such as those of Roger's. In the experiments now described the negative capillary pressure exerted by the surface of the soil is measured. To avoid confusion, the term " negative pressure " is used in the present paper.

The first series of experiments on negative pressure were carried out on different grades and comparatively short columns of soil, the main purpose here being to examine how far considerations of capillarity can be applied to actual soils. The second series of experiments were conducted with different heights of soils within and above the capillary height. In the third series of experiments, sand was packed in water, the length of the columns being less than the capillary height of the sand. The negative pressure was determined after covering the top of the wet sand with dry sand. The total length of wet and dry sand column was more than the capillary height of sand.

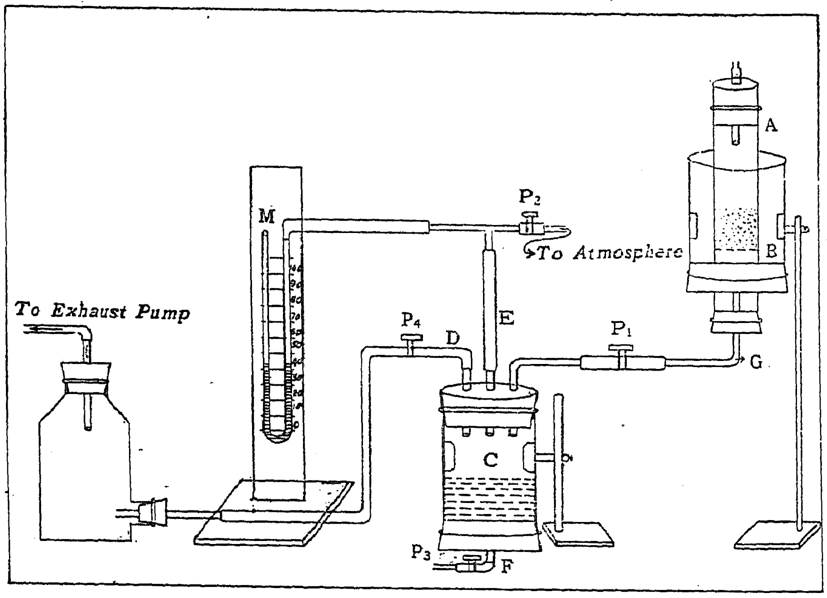

FIG. 1.
Arrangement to determine Negative Pressure in Soils

Experimental

The apparatus employed to determine the negative pressure of water in the soil is shown diagrammatically in Fig. 1. It consists of a glass tube AB with a piece of wire-gauze fixed at B. The tube G which comes out of the lower portion of the tube AB passes through a tube in the cork closing the mouth of the tube C. This tube G allows the water of the tube AB to fall into the tube C. The soil to be tested for negative pressure is put in the tube AB above the wire-gauze at B. Any length of the column of the soil can be experimented upon by varying the height of AB. D and E are two tubes connected, as shown in Fig. 1, one to a vacuum pump and the other through a T tube to a mercury or water manometer M. The tube E also enables the tube C to be opened to the atmosphere. Water can be removed from tube C with the help of tube F.

The wider tube surrounding the tube AB had a current of water at a constant temperature of 20° C. flowing through it so as to avoid temperature fluctuations in the soil contained in the tube AB.

The tube AB is first filled with water from below in order that there should be no air in the tube G or in the portion of tube AB below B. The pinch-cock P_1 is then closed and the soil to be tested put into the tube AB. After the soil has been packed in the tube under water, the pinch-cock P_1 is opened and the water begins to drop into tube C from tube G. When the plane water surface reaches the soil surface, the water film in the uppermost layer of the soil exerts a tension and water stops dripping through the end of the tube G. The pressure in C is then decreased till water again starts dripping through the end of the tube G. This takes place when the water film at the surface of soil just breaks. The reading of the manometer M is observed at this point. This gives the negative pressure when the plane water surface at the top of the sand column just breaks.

Results

In the first series of experiments on pressure deficiency, twelve graded samples were investigated. These samples ranged from very coarse sand to very fine silt containing clay.

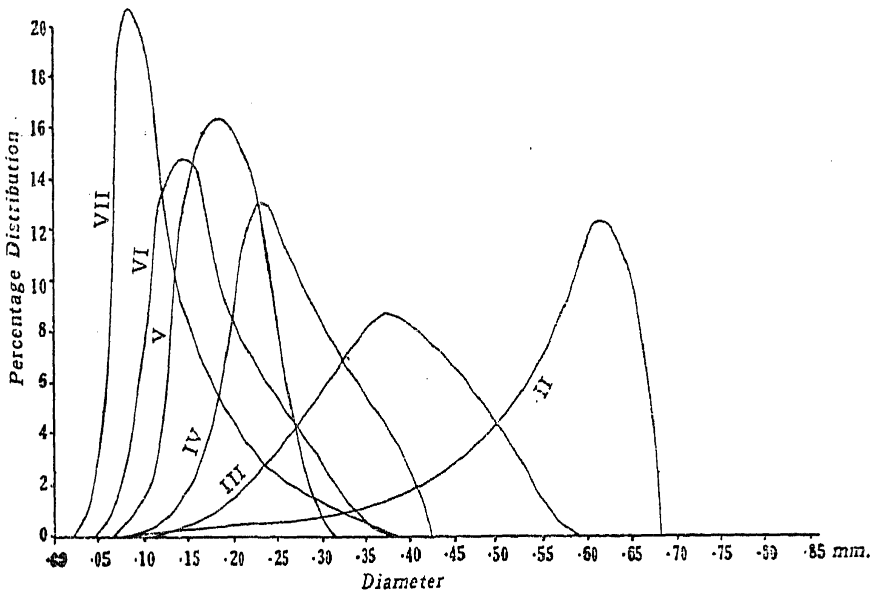

FIG. 2

Size Distribution of Sands

Nos. II to VII

Mechanical analysis of samples.—The mechanical analysis of these samples is shown in Table I and Fig. 2, the analysis of samples 2 to 7 was obtained by the optical lever siltometer[1] and the size distribution curves are given in Fig. 2. Sample No. 1 was analysed with the help of sieves of

TABLE I

Sample No.	Percentage size distribution					Negative pressure in cm. of water	Percentage moisture content	$K = \frac{\rho g h \cdot 2r}{T}$	Statistical mean diameter
	0·50–0·60 mm.	0·60–0·88 mm.	0·88–1·00 mm.	1·00–1·32 mm.	1·32–1·50 mm.				
1	0·24	15·57	29·81	51·84	2·63	11·8	21·5	Could not be calculated	
2		Curve 2 in Fig.				15·2	22·2	11·5	0·545
3		,, 3 ,,				24·1	23·8	11·89	0·374
4		,, 4 ,,				36·4	24·7	12·62	0·264
5		,, 5 ,,				49·2	24·4	12·46	0·191
6		,, 6 ,,				72·9	25·0	16·50	0·167
7		,, 7 ,,				86·3	24·4	14·96	0·132
	Below ·002 mm.	·002–·02 mm.	·02–·2 mm.						
8	0·05	4·51	88·72	The remaining contains organic matter		181·5	24·5	Could not be calculated	
9	9·18	54·85	19·67			200·7	37·7	,,	,,
10	17·8	58·08	17·65			313·9	39·1	,,	,,
11	1·01	43·59	57·19			391·2	35·5	,,	,,
12	67·81	19·02	10·10			562·1	47·5	,,	,,

different mesh sizes, this being too coarse to be analysed by the optical lever siltometer. Samples Nos. 8 to 12 were mechanically analysed by the pipette method, these being too fine to be analysed by the siltometer. Fig. 3 shows the photomicrographs of these samples with a magnification of 1 : 4.

Capillary height of the samples.—The negative pressure of these samples as determined by this apparatus is given in Table I. It shows that the finer the soil the greater the pressure deficiency.

The moisture content of the soil when the water just stops dripping from the end of the tube G was also determined. This is the stage at which the negative pressure was determined. The result is given in Table I.

In the second series of experiments two specimens of sand were examined with different columns to examine the effect of varying the length of the column. The mechanical analysis of the specimens of sands (*a*) and (*b*) are given in Fig. 4. The results are given in Table II.

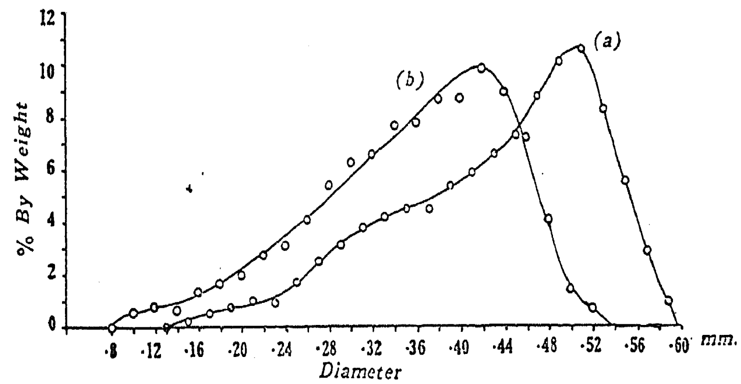

FIG. 4

TABLE II

Height of column	Negative pressure in cm. of water	Height of column	Negative pressure in cm. of water
Sand (*a*)		*Sand* (*b*)	
cm.	cm.	cm.	cm.
5	24	5	32
20	25	20	33
31	23	31	31
50	22	50	30

In the third series of experiments dry sand was introduced on the top of the wet column and the negative pressure was determined after different intervals of time. The object here was to ascertain the effect of dry sand on the capillary column. The results are given in Table III.

TABLE III

Column of wet sand	Column of dry sand	Time	Negative pressure in cm. of water
	Sand (a)		
cm.	cm.		
20	15	5 mts.	27
20	15	1 hour	26
20	15	2 hours	26
20	15	4 ,,	26
20	15	24 ,,	27
20	15	72 ,,	27
	Sand (b)		
20	15	5 mts.	40
20	15	1 hour	41
20	15	2 hours	40
20	15	4 ,,	36
20	15	72 ,,	39

Discussion of Results

The first series of experiments was carried out on samples of sand many of which have been analysed for their particle size by the optical lever siltometer. Their mean diameters have also been worked out and they are given in Table I. The object here was to examine whether the treatment of pore spaces as applied by Slichter can be extended to natural sands.

Slichter[2] treated the pore space in soil particles as a bundle of capillary tubes with an approximately triangular cross-section, assuming the soil particles to be spherical. The mean value of the triangular cross-section was calculated by him as $0 \cdot 2118\ r^2$ where r is the radius of the soil grain, which is spherical and all grains are supposed to be of uniform size. Keen[3] using this idea of the triangular pore space has worked the formula $\rho gh = KT/2\,r$

where ρgh is called the pressure deficiency. Here ρ is the density of the liquid; g is gravity; h is the height to which the liquid rises; K is the capillary coefficient, T is the surface tension and r is the radius of the grain. This is considered as the fall of pressure in passing from air through the liquid meniscus. Hacket and Stratten called K in the above equation the capillary coefficient. The value of K according to Keen is 19·8. Hackett[4] in experiments on the ascent of oils through sands found that the average value of K was 7·84. Working on glass spheres with benzene as the liquid, he found that the value of K was 9·76. He also calculated the value of K theoretically for a close packing and for cubical packing. The value of K for close packing is 25·86 and for a cubical packing the value of K is 9·66.

Table I gives the values of K determined from the pressure deficiency in the present experiments. If we calculate K for these soils, from their statistical mean value of the diameter m, there is no agreement.

The capillary theory of a bundle of tubes cannot therefore apply to natural soils and any conclusions derived from such a consideration must therefore be wrong. It is certainly true that capillary forces do exist in soil moisture relations, but to consider a natural soil as a bundle of capillary tubes and deduce relations from these is not correct. In the case of natural soils considerations similar to those on uniform spheres do not have a quantitative application.

The second series of experiments indicate that the pressure deficiency is independent of the length of the column, within what is called the capillary height.

The third series of experiments indicate that even if the column of soil is greater than the capillary height, there is no effect on the negative pressure. This is a point of importance to problems of irrigation, because it has been assumed that the presence of dry or wet soil on the top surface brings about considerable changes in the soil moisture relations at or near the water-table. The experiments conducted here show that it does not.

As has been shown in a previous investigation,[5] conditions at the surface do release pressure and cause apparent fluctuations in the water-table, but they do not change the moisture relations of the soil above the water-table. These remain mostly in the original condition, *i.e.*, the presence of the dry soil does not appear to change the moisture gradient near the water-table to any appreciable extent. Experiments conducted by Dr. E. McKenzie Taylor[6] seem also to indicate to similar conclusions. Further investigations are in progress and will be reported subsequently.

We have great pleasure in thanking Dr. E. McKenzie Taylor for his keen interest in the problem.

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