STUDIES ON SOIL PHYSICS.

PART I.—THE FLOW OF AIR AND WATER THROUGH SOILS.

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Introduction.

§ 1. In connexion with a research on the composition of drainage waters from soils, which is now being undertaken at this laboratory, it was found advisable to have some definite knowledge of the permeability of the soils to water.

The mechanical analysis of soils, as ordinarily carried out, determines the percentages of the various sized particles present; but this determination in the majority of cases gives only indirect and approximate information as to its properties. For example, we know, in a general way, that a soil containing a large percentage of clay will be only slightly permeable to air or water, and conversely, if it be composed mainly of coarse particles, it will usually be open and easily drained; but the presence or absence of humus material may have an altogether indeterminable effect on these properties if we have merely the usual mechanical and chemical analyses to guide us.

In any case such knowledge is at best only qualitative, whereas the information actually required in the above instances—indeed in any investigation dealing with drainage, irrigation or loss by evaporation—should quantitatively express the relations of the soil to the movements of air and water through it.

These relations are much less obscure if we direct our attention to the number and dimensions of the spaces between the particles rather than to the sizes of the particles themselves.

It will be shewn that the information required can be supplied for a given soil by a knowledge of three quantities which may be regarded, and recorded, as specific constants of the soil.

§ 2. *Definitions of Soil Constants.*

(*a*) The *Specific Pore* or *Interstitial Space*, designated by S, may be defined as the free space per unit volume of soil.

(*b*) The *Permeability* to *Water*, designated by P_w, may be measured by that volume of water which will pass per second, through a soil column of unit length and of unit area of cross-section when under one centimetre head of water pressure. The *Permeability* to *Air* may be similarly defined and is designated by P_a.

(*c*) The *Capillarity Coefficient*, designated by K, may be defined as the tension due to capillary forces per unit area of cross-section of the pore-spaces which tends to draw the water from the saturated to the dry region of the soil.

§ 3. King has indeed suggested the direct measurement of the permeability but he uses the data so obtained to calculate the average size of the soil particles, without insisting on the intrinsic value of the permeability constant itself.

This paper describes our attempts to construct a scientific basis for these three fundamental constants and includes an account of the methods adopted for their measurement and the results obtained with three types of soil.

§ 4. These constants are constants for a particular soil in a particular condition; they are however all interdependent, and are liable to considerable alteration when the soil is disturbed as by the ordinary farm operations of ploughing, rolling, etc., or by the ordinary process of taking the sample. Alterations are also caused by variations in the water content.

Obviously, therefore, the measurements should be made on the soil *in situ*, although our preliminary experiments have been made on "disturbed" samples.

The perfection of a method of soil sampling which will not disarrange the original structure, etc., is greatly to be desired, as it would render possible the comparison of the relative efficiency of various methods of cultivation—to mention one of many applications. An instrument has indeed been devised for this purpose by Stevenson[1], but the present writers have as yet had no opportunity of testing its suitability for their purpose.

[1] Iowa Agric. Expt. Station, U.S.A., *Bul.* 94, 1908.

Theoretical Development and Discussion of the Soil Constants.

§ 5. (*a*) *The Specific Pore Space.*—The *accurate* calculation or measurement of this factor is a far from satisfactory problem when complicated by the ordinary field conditions, and both the permeability and the capillarity of the soil shew considerable variations for a small difference in its value.

In the experiments (to be described in a further paper) with practically uniform spherical glass beads of 0·25 to 1·0 mm. diameter, the pore space varied from 0·40, when the beads were simply poured into the containing vessel, to 0·35, when they were compacted as far as was possible by rolling and tapping. In the latter state the permeability was found to have been reduced to about 60 per cent. of its original value.

For soils, the specific pore or interstitial space—*i.e.* the free space per unit volume of soil—may be considered either as the actual space available for the interstitial air (S_a) or else as the total space not occupied by the solid matter of the soil (S_w). The usually slight difference between these two, in moderately dry laboratory samples, is of course due to the moisture present covering each grain of soil with a thin film of water and cutting down the free space available for air, and

$$S_w = S_a + \theta,$$

where θ is the volume of water present per c.c. of soil.

In a wet or waterlogged soil S_a may be only a small fraction of S_w.

In this research the specific pore-space, unless otherwise indicated, has been taken to mean S_a.

§ 6. (*b*) *The Permeability to Air and Water.*—We may regard a porous soil as composed of a bundle of capillary tubes, irregular in area, length, direction and shape, but sufficiently minute to reduce the velocity of flow of air or water, under normal conditions, to velocities which conform to Poiseuille's capillary tube law:

$$v = \frac{\pi}{8} \cdot \frac{ghst}{\eta} \cdot \frac{r^4}{l} \qquad \text{(1)},$$

where v = volume of liquid passing in time t;

and s = density of liquid;

r = radius of capillary;

η = viscosity of liquid;

l = length of capillary;

g = gravitational constant;

h = head of liquid pressure.

But for a soil the capillaries must be treated statistically and r^4 replaced by Σr^4 to denote the sum of the fourth powers of the efficient average radii of the capillaries in the area of cross-section A under consideration.

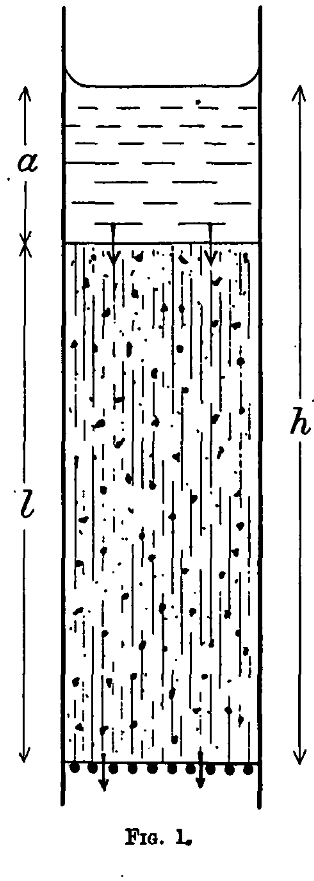

FIG. 1.

If we consider a vertical tube of soil (Fig. 1), of length l, through which water is flowing under the influence of a head of pressure $a + l = h$, and escaping freely at the lower end; then

$$\frac{v}{t} = \frac{\pi}{8\eta} \cdot \frac{ghs}{l} \cdot \Sigma r^4 \quad \text{.........................(2),}$$

but $v = Ax$, where x = the distance that any given cross-section of water (of area A) has moved in the time t; therefore,

$$\frac{x}{t} = \frac{\pi}{8\eta} \cdot \frac{ghs}{l} \cdot \frac{\Sigma r^4}{A} \quad \text{.........................(3)}$$

$$= c \cdot \frac{h}{l} \cdot p,$$

where $c = \frac{\pi gs}{8\eta}$ and $p = \frac{\Sigma r^4}{A}$ (the absolute permeability of the soil).

Then $$cp = \frac{x}{t} \cdot \frac{l}{h} = P_w \quad \text{.........................(4)}$$

or $$P_w = \frac{v}{t} \cdot \frac{l}{Ah} \quad \text{.........................(5).}$$

§ 7. P_w is the practical permeability constant of the soil for water, and is equal to the volume of water passing, in unit time, through a soil column of unit area of cross-section under a head of water pressure equal to the length of the column. It may also be expressed as "the linear rate at which water will sink through an area of soil, saturated and just covered with the water."

Whereas p, the absolute permeability, is independent of the temperature and depends only on the structure of the soil, P is inversely proportional to the viscosity of the permeating fluid and therefore, when water is employed, varies some two or three per cent. per degree centigrade.

§ 8. In measuring the permeability to air, P_a, Meyer has shewn that the working pressure ghs in equation (2) must be replaced by $q_1 - q_2$, where q_1, q_2 are the pressures (in absolute units) of air at the two ends of the column, or more correctly by $\frac{q_1^2 - q_2^2}{q_0}$, where q_0 is the pressure under which the volume v of the air is measured.

Various experimenters, including Darcy (1856), Hazen (1890), King and Slichter (1899), Bell and Cameron (1906) and Leather (1908) have made measurements on the permeability of soils to either air or water and have found that, with certain limitations to be discussed further, both the Poiseuille and Meyer-Poiseuille formulae hold good.

§ 9. From equation (3) $\eta_w P_w$ should be equal to $\eta_a P_a$; or p, the absolute permeability, should be independent of the fluid (water or air) experimented with unless the presence of the water is sufficient to modify the capillary passages of the soil.

A critical examination of the results obtained by King[1] and of the measurements to be here described, shew that this modification may take place in two ways: (i) by the moisture in the soil restricting the area of the capillaries through which the air is passing, and hence causing S_a to be less than S_w; and (ii) by the humus, clay or other colloidal matter of the soil absorbing water when the soil is wet. The consequent swelling may restrict or even completely close the capillaries in this case.

These considerations again emphasise the advisability of determining the permeability to air and water of the soil *in situ*, without disturbing either its structure or its moisture content.

§ 10. (c) *The Capillary Coefficient.*—Thus far we have considered the permeability of soils to water when they are already saturated, but under ordinary conditions soils are usually less moist than this and may sometimes be almost dry.

Capillary forces must therefore be taken into account, for they assist the hydrostatic pressure when the water is passing downwards and can, in the dry season, even cause moisture to rise to the surface against the force of gravity. The papers of Lyman Briggs, Buckingham and Cameron[2] and of Leather[3] are of great interest in this connexion.

To investigate the nature of the capillary constant we will, as before, consider a column of soil uniformly packed in a tube through which water is percolating from one end.

§ 11. There are three possible cases for consideration, according as the water is travelling vertically downwards or upwards, or horizontally sideways.

1. Of these three possibilities take first the case in which the movement is vertically downwards.

Then the impelling force at any instant will no longer be ghs as in equation (2) but $gs(h+K)$ where K is a constant of the soil depending on the capillary forces acting on the moving boundary of the water.

As the water only occupies the pore-space, S, of the soil it follows that at any stage the velocity of the water front will be given by the equation

$$\frac{dv}{dt} = A\frac{dl}{dt}S \quad \text{..............................(6)},$$

[1] *XVth Ann. Rep. Wisc. Agr. Expt. Station*, p. 123.
[2] U.S.A. Bureau of Soils, *Buls.* 10, 19, 30, 38, etc.
[3] *Mem. Dept. Agric. India*, 1908, Vol. I. 79.

where v and l as before represent respectively the volume of the water and the length of the wetted soil (Fig. 2).

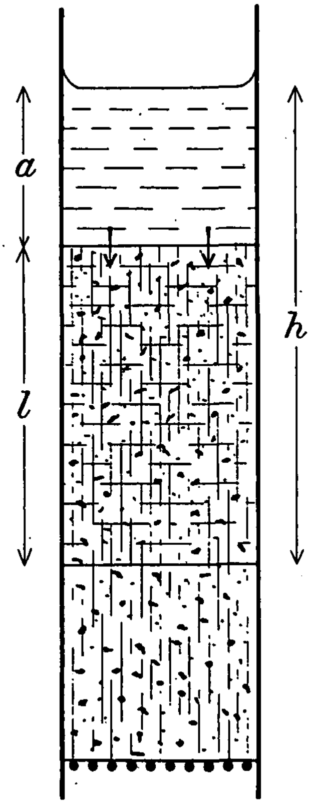

FIG. 2.

Then on the basis of equation (3), we get

$$\frac{dl}{dt}=\frac{\pi}{8\eta}\cdot\frac{gs(h+K)}{l}\cdot\frac{\Sigma r^4}{AS} \quad \text{..........(7)}$$

$$=\frac{cp}{S}\cdot\frac{h+K}{l}$$

$$=\frac{P}{S}\cdot\frac{h+K}{l} \quad \text{..........(8)};$$

therefore as $h=a+l$, and a, K, P and S are constants,

$$\frac{P}{S}t=\int_l^0\frac{l\,.\,dl}{l+a+K};$$

and, since $t=0$ when $l=0$,

$$\frac{P}{S}t = l - (a+K)\log_e\left(1+\frac{l}{a+K}\right) \qquad (9).$$

2. The second possibility comprises the case in which the water is rising vertically in the column of soil, under the influence of capillarity, and against the hydrostatic pressure.

If the lower end be just in contact with the water surface then $h=l$ and $a=0$ and the equation becomes

$$\frac{dl}{dt}=\frac{P}{S}\cdot\frac{K-l}{l} \qquad (10),$$

which on integration gives

$$\frac{P}{S}t = K\log_e\left(\frac{l}{K-l}\right) - l \qquad (11).$$

3. In the third possibility the motion is horizontal, and in this case is due entirely to capillary suction.

Hence

$$\frac{dl}{dt}=\frac{P}{S}\cdot\frac{K}{l} \qquad (12),$$

and integrating,

$$\frac{PK}{S}t=\tfrac{1}{2}l^2 \qquad (13).$$

This case is perhaps the most interesting, for not only is it often realized in the field (as when water is percolating from irrigation channels) but its experimental realization in the laboratory can be readily followed without the mathematical and other complications present in the two first cases.

§ 12. *Experimental tests of validity and further development of the formulae deduced in* § 11.—We have thus deduced three formulae representing the movement of water through dry soil in the three important directions, and the validity of these provisional formulae (9, 11, 13) has been tested experimentally in the following manner.

§ 13. A glass tube about one inch in diameter and thirty inches long was carefully and uniformly packed with air-dry loam to within six inches of the upper end; the lower end of the tube being closed with a disc of copper gauze supported by a perforated cork. A layer of water 10 cms. deep was placed on top of the soil column, and any deficiency caused by percolation of this water into the soil was made good by means of the usual constant level apparatus.

Readings were taken of the progress of the water downwards at intervals during sixty hours, at the end of which time water began to drip from the lower end of the tube.

From equation (9),

$$\frac{P}{S}=\frac{l-(a+K)\log_e\left(1+\frac{l}{a+K}\right)}{t}.$$

K was unknown, but a few trials showed that $K=90$ gave the best results.

The observed values of l were plotted against t, and the following results were obtained from the curve drawn through the experimental points:

TABLE I.

t (hours)	l (centimetres)	$\frac{P}{S}$
0·25	3·3	·20
0·5	4·6	·20
1	6·7	·206
2	9·7	·210
3	11·9	·227
4	14·0	·225
5	15·6	·218
10	21·7	·208
20	31·2	·202
50	52·4	·206
60	58·0	·204

§ 14. The same concordance was not obtained, however, when equation (11) was applied by us to a series of measurements carried out by Loughridge[1] on the rate of rise of water in a tube of soil.

In this case K was taken as 42·5, for that was the maximum height reached by the ascending water.

By equation (11),

$$\frac{K\log_e\left(\frac{K}{K-l}\right)-l}{t}=\frac{P}{S}=\text{a constant};$$

but the actual values calculated from the experimental readings shew that there is some factor which has not been taken into account.

[1] Hilgard, *Soils*, p. 205.

TABLE II.

t (hours)	l (centimetres)	$\dfrac{K \log\left(\frac{K}{K-l}\right) - l}{t}$
1	20·4	7·4
2	25·5	6·75
6	31	4·1
12	33	2·55
24	35·7	1·75
48	39	1·40
144	42·5	—

§ 15. In these calculations the water has been regarded as at once occupying the whole of the pore-space in each layer of the soil as it reaches it. This condition is apparently realised in the case of a downward flow of water; but when the percolation is upward or horizontal numerous experimenters have shewn that the percentage of moisture in the soil decreases continuously with the distance from the water supply.

The same difficulty has been recognised by Bell and Cameron[1], who have also investigated the rate of entry of water into capillary spaces. They found that for a single horizontal capillary tube the velocity of movement is in accord with equation (13),

$$\frac{l^2}{t} = C,$$

but for soils and other porous media the rate of movement of the visible water front could only be empirically represented by the equation,

$$\frac{l^n}{t} = C',$$

where n is generally greater than 2 but varies for each individual experiment.

They say: "In this latter case, however, there is no way of distinguishing between that portion of the substance which is merely wet by a capillary film of liquid over the grains or fibres, and that portion of the substance whose interstices are filled with the liquid."

§ 16. If, however, instead of modifying the foregoing equation by empirically altering n, it is modified in such a way as to take into account the fact that the length of moistened soil does not correspond

[1] *Jour. Phys. Chem.* 1906, x. 663.

with the real length of column traversed by the whole of the water, but is greater than this; then the difficulty will be found to disappear.

Consider the case of a horizontal soil column (in order to eliminate all but capillary forces), then the distribution of water will be as diagrammatically illustrated in Fig. 3, the foremost portion of the moist area being incompletely saturated and θ/s, the fraction of the soil pores occupied by water, being less than unity.

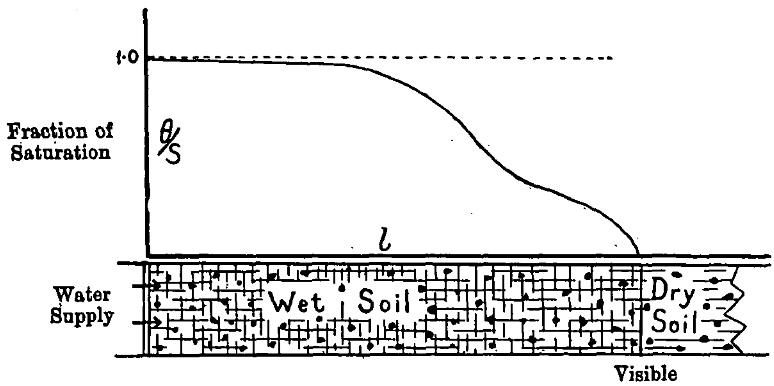

FIG. 3.

If we assume that the water present in this region is distributed uniformly among the fine and coarse capillaries then the average effective length of the soil column will be equal to $\frac{v}{AS}$, the volume of water which has entered the tube per unit area of cross-section of the soil pores. But $\frac{v}{AS} = \frac{m}{sAS}$ where m = the mass of water absorbed by the soil column, and s = density of water = 1 (with sufficient accuracy).

Substituting this quantity for l in equation (13), $\frac{2KP}{S} = \frac{l^2}{t}$, we obtain

$$2A^2KPS = \frac{m^2}{t} \quad \text{.........................(14)},$$

which should, even though not rigidly correct, give us a close approximation to the truth.

The following measurements were taken of both the rate of linear flow and the weight of water percolating into a soil tube:

TABLE III.

t (hours)	$\frac{l^2}{t}$	$\frac{m^2}{t}$	$\frac{\theta}{S}$
1	61·3	25·3	·804
2	56·9	25·9	·848
3	55·5	26·0	·860
6	53·9	26·3	·877
9	52·3	26·3	·890
12	49·0	25·9	·915
18	48·5	25·7	·915
21	48·0	25·7	·915
24	48·1	25·9	·923
26	48·3	26·0	·923

The superiority of equation (14) over equation (13) is conclusively shewn; the values of $\frac{l^2}{t}$ and of θ/s (the fraction of the pore-spaces of the wet soil filled with water) are such as would be expected from the foregoing considerations. The slight rise shewn in the later values of $\frac{l^2}{t}$, and less markedly of $\frac{m^2}{t}$, has been observed in almost every experiment, and may be accounted for by the effect of the viscosity of air, which steadily diminishes as the tube becomes filled with water.

§ 17. The constancy of $\frac{m^2}{t}$ as given in Table III. justifies the conclusion that the determination of the weight of water entering a horizontal soil column will lead us to a reliable and sufficiently accurate method of measuring KP_wS, and since S and P_w for the same column of soil can be determined independently, K can be evaluated by substituting their values in equation (14),

$$2A^2KP_wS = \frac{m^2}{t}.$$

Experimental Investigation.

§ 18. *The soils used.*—Three soils were used in these preliminary experiments.

A. A friable loam obtained from the grounds of the University of Melbourne, prepared by breaking up with a rubber pestle. It was spread out on paper to dry, when it was passed through a sieve of about 0·5 mm. mesh—the coarse grains and rootlets, etc., being rejected.

The moisture content of this air-dried loam was found to be 1·41 per cent. Its density was determined by weighing in a 50 c.c. specific gravity bottle with kerosene ($d\frac{18}{18} = 0·7993$).

9·796 grams of air-dry soil displaced 3·072 grams of kerosene and therefore had a specific gravity of 2·496. Similarly 14·851 grams of the same soil dried at 100° C. displaced 4·756 grams kerosene and had a specific gravity of 2·549. This observed difference is exactly that calculated from the water content of the air-dry soil.

B. A clay soil obtained from Werribee, Victoria, for use in a series of experiments in connexion with the influence of fertilizers on drainage.

This soil was only used in a few experiments.

C. A surface sand obtained from Canterbury, near Melbourne, which was sufficiently free from colloidal clay to serve as a type of a highly permeable soil.

§ 19. *Method of experimenting.*—For the purpose of experiment glass tubes were filled as uniformly as possible with the soil.

The difficulties involved in packing tubes with soil are well known and there is no satisfactory method of determining with what uniformity a tube of soil has been packed. Even two tubes having the same permeability may be very dissimilar in respect to the actual arrangement of the particles of soil.

The method of filling employed in these experiments is as follows: The end of the tube is first temporarily closed with a cork, then about two inches length of soil introduced at a time, and the tube rotated rapidly around its longitudinal axis and occasionally "dumped": too much jarring causes a visible separation of the smaller from the larger particles. In this manner the tube is filled; the other cork is then pressed home, and alternate rotation and jarring continued until there is no further sign of closer packing. These temporary corks are now removed and the soil is kept in position by accurately fitting discs of filter paper and fine copper gauze backed up by perforated cork plugs carrying glass connecting tubes. Finally the corks and tubes were sealed in position with ceresin or paraffin wax as in Fig. 4.

Direct measurements shewed that the resistance offered by the discs of filter paper and gauze was negligible compared with that of a few centimetres of soil.

§ 20. In the first experiment, the results of which have already been given in Table III., the tube used had a mean diameter of 3·23 cm. and was filled to a length of 58 cm.

As the amount of soil introduced into the tube was not weighed it was impossible to calculate the pore-space S and so obtain an exact value for P, but it will be observed that the water had reached the lower end of the tube in 60 hours.

A similar tube was at the same time filled with the clay soil. Here the downward progress of the water was at first rapid, but after a few minutes became extremely slow, and the advancing line of moisture shewed less and less distinctly until it was eventually practically invisible. An indication was however obtainable that the water had reached the lower end of the column in about eleven months; this gives an approximate idea of the relative permeabilities of the loam and the clay.

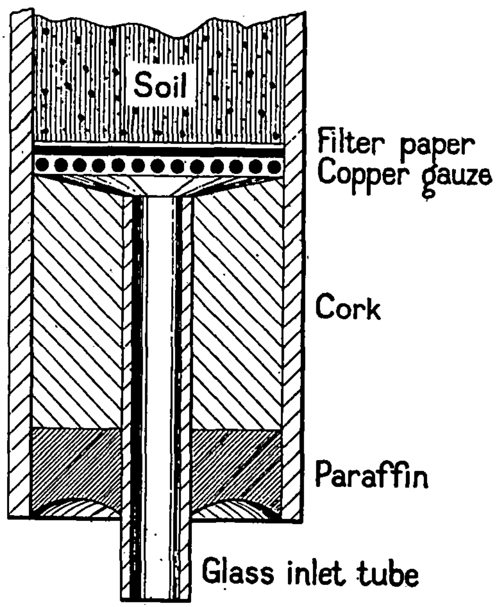

FIG. 4.

§ 21. *Procedure recommended for the "physical examination" of soils.*—In later experiments weighings were taken not only of the soil used but also of the water absorbed, and the following method of procedure was adopted for the "physical examination" of soils:

§ 22. (1) *Determination of the Specific Pore-Space* (S).—The soil was filled into the tube in the manner described, and weighed; the length (l) of the soil column was then measured and from the area of cross-section (A) of the tube (previously determined from the water content of a convenient length), and from the specific gravity of the soil, the value of S can be calculated.

$$S = 1 - \frac{W}{Al\Delta},$$

where W is the weight and Δ the specific gravity of the soil.

The value of S affords interesting information as to the degree of compactness to which it is possible to pack the soil under the uniform conditions described.

§ 23. (2) *Determination of Permeability to Air.*—The soil tube is now attached by a short caoutchouc tube to an ordinary nitrometer containing water instead of mercury. An increased or diminished pressure can be obtained by appropriate adjustment of the water level in the two limbs and thus air may be forced through the soil tube in either direction.

Both pressure and suction are employed and the times of passage of certain volumes of air, as measured on the nitrometer scale, observed.

It is obvious that the pressure is constantly altering, but the relationship between the pressure (difference in levels) and the volume (indicated by the scale reading) is easily established for $h = h_0 \pm bv$, where h_0 is the initial pressure and b is a constant for the particular nitrometer tubes employed.

From equation (5),

$$P_a = \frac{dv}{dt} \cdot \frac{l}{Ah},$$

and as $h = h_0 \pm bv$, then on integrating between the limits h_1 and h_2, *i.e.* t_1 and t_2; we get

$$P_a = \frac{\log_e\left(\frac{h_1}{h_2}\right) . l}{(t_2 - t_1) Ab}$$

$$= \frac{2{\cdot}303l.}{A . b} \cdot \frac{\log_{10}\left(\frac{h_1}{h_2}\right)}{t_2 - t_1} \quad \text{..................(15).}$$

The question as to whether concordant results could be obtained with either "head" or "tail" of pressure was conclusively answered by the following set of readings, and any corrections, such as are required when dealing with a single capillary tube (or higher pressures), are shewn to be unnecessary with ordinary soils for the low pressures used.

TABLE IV.

Permeability of Soil to Air.

Using "head" of pressure				Using "tail" of pressure			
v (c.c. of air)	t (minutes)	h (cm. of water)	$\frac{\log_{10}\left(\frac{h_0}{h}\right)}{t}$	v (c.c. of air)	t (minutes)	h (cm. of water)	$\frac{\log_{10}\left(\frac{h_0}{h}\right)}{t}$
0	0	+32·2	—	0	0	−30·0	—
2	·51	29·0	·0892	2	·55	26·8	·0891
6	1·70	22·7	·0893	5	1·52	22·0	·0886
9	2·88	17·9	·0885	7	2·28	18·8	·0889
10	3·81	14·8	·0885	11	4·32	12·5	·0880
12	4·38	13·2	·0884	12	4·99	10·9	·0881
13	5·00	11·7	·0879	13	5·79	9·3	·0878
14	5·71	10·1	·0882	14	6·76	7·7	·0874
15	6·56	8·5	·0882	15	7·89	6·1	·0877
16	7·58	6·9	·0883			Average...	·0882
		Average...	·0885				

But by taking h_1 and t_1 as the initial pressure and time in each calculation any error at that point will affect every observation, and so in later experiments a fresh starting point was taken for each calculation.

§ 24. A more convenient and accurate arrangement of apparatus was also devised in which the graduated limb of the nitrometer was replaced by an inverted burette with a two-way tap and the other limb by a large water reservoir. The pressure corresponding to any burette reading is given by the difference in level of the water in the burette and in a short gauge tube of the same diameter attached to the connecting tube by a T-piece. (See Fig. 5.)

In order to avoid inconveniently long or short times of flow the diameter or length of the tube used to contain the soil should be selected to suit its permeability.

The water level is first adjusted to the 25 c.c. mark on the burette with the tap open to the air, and then by applying suction the level is raised several centimetres above the 50 c.c. mark. The tap is then turned to communicate with the soil tube, and the stop-watch started as the water passes the 45 c.c. mark and time readings taken over a range of 15 c.c. when the watch is stopped at the 30 c.c. mark.

Similarly a set of readings are taken between the 5 and 20 c.c.

marks, when the air will be drawn through the soil tube under a "tail" of pressure.

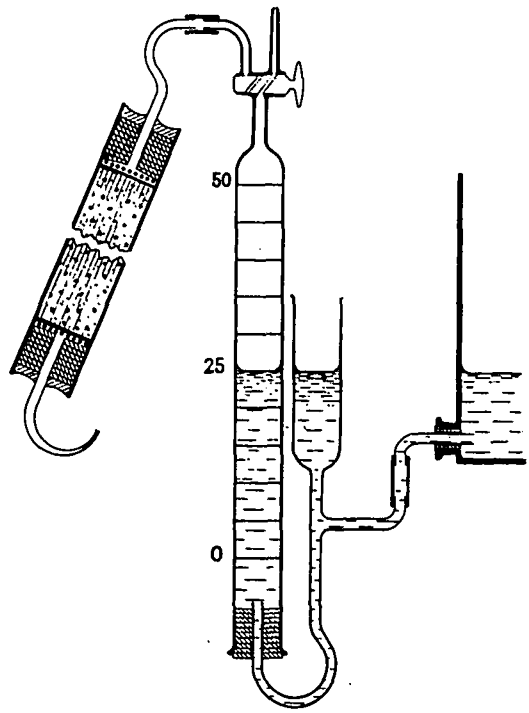

FIG. 5.

The observations recorded in Table V. were taken with both "head" and "tail" of pressure on a tube filled with loam.

Although values of $\frac{\delta v}{\delta t} \cdot \frac{1}{h}$ and consequently of P_a can be obtained by taking the differences between consecutive readings in this way, a more systematic method of utilizing such a series of observations is that given in Table VI. As the values of $\log_{10}\left(\frac{h_1}{h_2}\right)$ have only to be determined once for each apparatus, this method of calculation is probably the simplest in practice and certainly the most satisfactory.

Considering the probable calibration errors of an ordinary nitrometer (such as was employed in these experiments) the *accuracy* of this method of determining the permeability of a column of soil is beyond criticism and the simplicity of the apparatus and measurements required give it an important advantage over the methods usually employed for that purpose.

TABLE V.

Calculation of Permeability Constant from Experimental Results.

v (c.c.)	t (minutes)			h (cm.)	$\frac{\delta v}{\delta t} \cdot \frac{1}{h}$
	Head	Tail	Mean		
0	0	0	0	31·68	
2	·600	·590	·595	28·52	0·1116
4	1·265	1·260	1·263	25·35	0·1111
5	1·63	1·63	1·63	23·77	0·1110
6	2·03	2·01	2·02	22·19	0·1117
7	2·44	2·43	2·435	20·36	0·1127
8	2·89	2·90	2·895	19·01	0·1098
9	3·38	3·40	3·39	17·42	0·1109
10	3·925	3·925	3·925	15·84	0·1124
11	4·51	4·55	4·53	14·26	0·1099
12	5·16	5·23	3·195	12·67	0·1118
13	5·89	6·02	5·955	11·09	0·1107
14	6·75	6·91	6·83	9·50	0·1111
15	7·71	8·02	7·865	7·92	0·1109
				Average...	0·1112

$$P_a = \frac{l}{A \,.\, 60} \cdot \frac{\delta v}{\delta t} \cdot \frac{1}{h} = \frac{35·05 \times ·1112}{1·950 \times 60} = 0·0333.$$

TABLE VI.

Calculation of Permeability Constant from Experimental Results.

v_1 v_2	t_1	t_2	$t_2 - t_1$	$\log_{10}\left(\frac{h_1}{h_2}\right)$	$\frac{\log_{10}\left(\frac{h_1}{h_2}\right)}{t_2 - t_1}$
0— 9	0	3·390	3·390	·2597	·0764
2—10	0·595	3·925	3·330	·2554	·0766
4—11	1·263	4·53	3·287	·2499	·0763
5—12	1·63	5·195	3·565	·2732	·0764
6—13	2·02	5·955	3·935	·3012	·0765
7—14	2·435	6·83	4·395	·3353	·07623
8—15	2·895	7·865	4·970	·3803	·0766
				Average...	·07643

$$P_a = \frac{2·303 l}{60 \,.\, Ab} \cdot \frac{\log_{10}\left(\frac{h_1}{h_2}\right)}{t_2 - t_1} = \frac{2·303 \times 35·05 \times ·07643}{60 \times 1·950 \times 1·585} = ·03325.$$

§ 25. (3) *Measurement of Capillary Flow.*—The tube is now placed in a horizontal position with the sickle-shaped inlet tube dipping into a dish of water, the surface of which is adjusted to the same level as the axis of the soil column.

A slight suction is now applied at the far end so as to fill the inlet tube with water. Percolation immediately starts and its progress is measured at convenient intervals by weighing the soil tube rapidly and keeping it in the horizontal position so as not to interfere with the percolation.

The distance to which the visible water front has penetrated may also be measured, several readings being taken to obtain its mean position when its progress on different sides of the tube is irregular, as is the case when the packing is not uniform.

TABLE VII.

Calculation of Capillary Constants from Experimental Results.

Temp.	t hours	Tube A				Tube B			
		l	m	$\frac{m^2}{t}$	$\frac{\theta}{S}$	l	m	$\frac{m^2}{t}$	$\frac{\theta}{S}$
15°·1	0·5	5·56	3·44	23·7	·775	5·66	3·35	22·5	·717
15°·3	1	7·83	5·02	25·3	·805	7·82	4·73	22·4	·722
15°·4	2	10·67	7·20	25·9	·846	10·80	6·81	23·2	·754
14°·8	3	12·90	8·84	26·0	·859	13·12	8·44	23·8	·768
13°·8	4	14·69	10·17	25·8	·869	14·79	9·76	23·9	·788
13°·5	6	17·98	12·55	26·3	·875	17·50	11 99	24·0	·818
12°·6	9	21·66	15·38	26·3	·890	21·34	14·69	24·0	·822
11°·5	11·67	23·87	17·39	25·9	·913	24·22	16·59	23·6	·817
11°·9	14	25·98	18·97	25·7	·917	26·30	17·95	23·0	·815
11°·4	18	29·52	21·49	25·7	·914	29·16	20·35	23·0	·835
12°·8	21	31·75	23·23	25·7	·918	31·28	21·95	23·0	·838
13°·2	23·1	33·30	24·42	25·8	·920	32·58	23·05	23·0	·846
13°·3	25	34·73	25·47	25·9	·921	33·85	24·03	23·1	·848
13°·5	26·2	35·58	26·11	26·0	·920	—	—	—	—
13°·5	27	—	—	—	—	35·17	24·97	23·1	·848
13°·4	27·8	—	—	—	—	35·70	25·38	23·2	·850
Saturated...		—	28·36	—	1·000	—	29·87	—	1·000
		—	—	*25·85*	—	—	—	*23·25*	—

Tube A. $KPS = \frac{m^2}{t} \cdot \frac{1}{2A^2} = \frac{25 \cdot 85}{3600 \times 2 \times (1 \cdot 950)^2} = 0 \cdot 000944.$

Tube B. $KPS = \frac{m^2}{t} \cdot \frac{1}{2A^2} = \frac{23 \cdot 25}{3600 \times 2 \times (1 \cdot 962)^2} = 0 \cdot 000838.$

These measurements of l are not required for the calculation of K, but are of interest as shewing the distribution of water in the "wet" soil.

§ 26. The experiments detailed in Table VII. were carried out simultaneously on two tubes filled with loam in slightly different states of compactness, and illustrate the degree of accuracy to be expected.

The small discrepancies in the values of $\frac{m^2}{t}$ can be largely accounted for by the effect of changes of temperature[1] on the viscosity of the percolating water; another possibility of slight error is the uncertainty in the initial readings and the correction for capacity of the inlet tube.

The figures in the columns headed $\frac{\theta}{S}$ denote the fractional saturation of the wetted portion of the soil. Both tubes had been as uniformly and similarly packed as possible, but the difference in the observed values of KPS is quite appreciable—0·00094 and 0·00084—and is due to the different values of S—0·475 and 0·4635.

§ 27. (4) *Saturation of the Soil in the Tube.*—After the whole soil column has become wetted the tube is turned up and the inlet (at the lower end) connected with a reservoir of water kept at a higher level than the top of the soil. After some time water begins to flow from the upper end of the soil, and, the outlet having been bent over and drawn out somewhat, this issuing water can be collected and weighed or measured without loss.

Weighings of the tube are made from time to time until no further increase is observed. This gives the amount of water required to saturate the soil and enables a comparison to be made with the value of S as determined in § 22 from the volume and weight of the soil column. The discrepancy usually found is due to incomplete expulsion of the air from the interstices of the soil.

§ 28. (5) *Measurement of Permeability to Water.*—The water reservoir is now adjusted at a convenient height above the level of the outlet from the soil tube and the permeability of the soil to water (P_w) calculated from the rate of flow.

$$P_w = \frac{v}{t} \cdot \frac{l}{Ah} \quad \ldots\ldots\ldots\ldots (5).$$

[1] Recently some experiments have been carried out on tubes kept in a draught-cupboard whose temperature was maintained at 20° by means of a gas burner and thermostat. The values obtained for $\frac{m^2}{t}$ shewed the expected improvement.

The usual method of measuring permeability is to measure the downward flow, but the rate of flow under these conditions constantly decreases on account of the silting which takes place with ordinary soils. In one tube, the rate of flow became practically zero at the end of three months. This difficulty is overcome by causing the water to flow upwards through the soil and by only employing moderate pressures.

The figures given in Table VIII. were those actually obtained from two different tubes of similar soil.

TABLE VIII.

Comparison of Upward and Downward Flow of Water for Measurement of Permeability.

Downward Flow. Pressure=76·6 cm.		Upward Flow. Pressure=20 cm.	
Time	Rate per hour	Time	Rate per hour
1 hour	7·85 c.c.	7 hours	0·32 c.c.
4½ hours	5·70 ,,	21 ,,	0·32 ,,
21 ,,	3·49 ,,	67 ,,	0·30 ,,
68 ,,	2·47 ,,	96 ,,	0·28 ,,
90 ,,	·80 ,,		
330 ,,	·09 ,,		

§ 29. (6) *Statement of results.*—Having thus measured S, $P_w KS$ and P_w directly, K can be calculated and the three important constants (S, P_w and K) controlling the flow of water through the soil should be tabulated.

The structure of its pore-spaces is more definitely described in this way than by any enumeration of the percentages of the various sized particles of which it consists.

§ 30. The permeability to air should also be tabulated, as on it depends the natural aeration of the soil, and in this connexion a further important relation is given by $\frac{\eta_a P_a}{\eta_w P_w}$. This ratio of the intrinsic permeabilities of soil to air and to water depends on the colloidal matter present and will vary from unity for a clean sand to fourteen or more for a clay soil packed as described above.

Experimental Results for Three Typical Soils.

§ 31. A number of experiments were carried out on these lines on each of the three soils described above and the results tabulated in Tables IX. and X.

TABLE IX.

The variation of Permeability with Specific Pore-space.

No.	Soil	Condition	θ	S	P_a
1	A. University Loam	Moist	·064	·493	·0356
2	,,	Air-dried	·020	·445	·0334
3	,,	Dried at 100°	—	·412	·0193
4	,,	Air-dried	·0184	·490	·0433
5	,,	,,	·0192	·467	·0333
6	,,	,,	·0192	·466	·0393
7	,,	,,	·0193	·463	·0348
8	,,	,,	·0194	·461	·0296
9	,,	,,	·0196	·454	·0291
10	,,	Dried at 100°	—	·495	·0450
11	,,	,,	—	·478	·0405
12	,,	,,	—	·475	·0315
13	,,	,,	—	·467	·0333
14	,,	,,	—	·4635	·0317
15	B. Werribee Clay	Air-dried	·0302	·431	·0312
16	,,	,,	·0303	·428	·0336
17	,,	,,	·0305	·423	·0285
18	C. Canterbury Sand	Air-dried	·0050	·379	·302
19	,,	,,	,,	·378	·274
20	,,	,,	,,	·373	·2795
21	,,	,,	,,	·373	·251
22	,,	,,	,,	·372	·245
23	,,	,,	,,	·368	·233
24	,,	,,	,,	·367	·262
25	,,	,,	,,	·363	·252
26	,,	,,	,,	·363	·248
27	,,	,,	,,	·362	·248

Both the pore-space (S) and permeability (P_a) in Experiments 1—3 in Table IX. show clearly the effect of moisture on the packing of a soil.

The dependence of the permeability on the specific pore-space is clearly shown by Experiments 4—9, 10—14 and 18—27 in the same Table.

It will there be seen that the specific pore-space is not the only controlling factor, for the discrepancies are greater than can be accounted for by experimental error. This same phenomenon was also noticed in measurements on spherical glass beads, and it would appear that the system of arrangement of the particles has some influence on

TABLE X.

Summary of Experiments with Typical Soils.

		University Loam					Werribee Clay			Canterbury Sand	
Specific pore-space	S	·495	·463	·467	·4635	·475	·431	·428	·423	·362	·363
Length of soil column	l	35·4	36·0	35·05	35·7	35·6	37·6	38·5	37·15	73·8	67·45
Area of cross-section	A	1·962	1·912	1·950	1·962	1·950	1·935	1·802	1·842	1·324	1·376
Weight of soil	—	88·46	91·99	91·69	94·93	92·72	107·8	103·2	102·7	162·8	152·8
Permeability to air..................	$P_a \times 10^3$	45·0	34·8	33·3	31·7	31·5	31·2	33·8	28·6	248·0	252·0
Percolation experiment...........	$\frac{m^2}{t} \times 10^3$	1·8	6·0	6·3	6·5	7·2	4·75	5·2	2·62	—	25·3
,, ,, ...	$KPS \times 10^3$	—	—	—	·84	·94	—	—	—	—	—
Permeability to water..............	$P_w \times 10^3$	·182	·159	·175	·122	·081	·036	·045	·033	2·05	2·1
Capillarity constant	K	—	—	—	—	—	—	—	—	—	—
Ratio of intrinsic permeabilities as determined by air and water	$\frac{\eta_a P_a}{\eta_w P_w}$	3·5	3·6	3·1	4·1	6·0	14·2	12·3	14·2	2·0	2·0

the permeability as well as the average specific pore-space of the column.

§ 32. In considering these tables of results it must be borne in mind that none of the soils were in their natural condition; *e.g.* the loam samples had, with one exception, been dried and contained no moisture at the start of the experiment, whilst the clay had been air-dried and only contained 2·0 per cent. of water, and the sand had also been partially dried.

Notwithstanding this the different soils differ markedly in their constants, thus one characteristic feature shewn by the clay soils is the high value given for the ratio $\frac{\eta_a P_a}{\eta_w P_w}$, indicating that the water has the effect of swelling out the colloidal matter in the soil and so constricting the capillary passages. This ratio should be unity for soils composed of pure sand; experiments, on that medium and on glass beads, to be described in a subsequent paper, have given identical results for $\frac{\Sigma r^4}{A}$, whether calculated from P_a or P_w (*vide* § 9).

§ 33. Whilst more valuable when carried out on a natural soil *in situ*, these measurements of the percolation factors can also yield considerable information when applied to disturbed samples of soil, such as are ordinarily sent in to the laboratory for "analysis."

Only about one hundred grams are required, and it is suggested that the soil should be prepared by careful air-drying, and reducing to powder with a rubber pestle in the usual way when in a friable condition. The soil tube should then be packed as tightly and uniformly as practicable with this air-dry soil after all particles larger than .1 mm. in diameter have been removed.

Summary.

§ 34. 1. The permeability and capillarity constants of soil have been defined.

2. The movements of air and water through three types of soil have been measured and shewn to conform to equations connecting the rate of motion with the above constants.

3. It is suggested that the measurement of S, P_a, P_w and K is of more importance than, and should replace, the determination of the sizes of the soil particles as in the usual "mechanical analysis" of soils.

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