# THE MOVEMENT OF SOIL WATER ABOVE AND BELOW THE WATER TABLE*

## (A GUIDE FOR FARMERS AND SCIENTISTS)

By A. D. WALSH SPARKS

### Introduction

Moisture above the water table can exist in the form of regions of water liquid and in the form of water vapour. The movement of moisture above the water table is therefore a complex movement of liquid and vapour.

The movement of water below the water table is easier to analyse because the water exists only as a liquid.

The water table (or phreatic surface) is the water level which can be determined in a well or bore-hole.

### Types of Water Table

Under certain circumstances it is possible to find more than one water table at a particular site. For example, in Figure 1, a clay lens JK intercepts rain water which is percolating downwards from the soil surface. Consequently a mass of water collects above this clay lens. This water will have its own water table which is known as a perched water table. The level of this water table would be given by the water level in borehole F.

A deep borehole G which misses the clay lens, would locate the deep water table (No. 2). Similarly in a lined pipe H which passes through the clay lens the water would rise only to the level of water table 2.

In many practical problems the water table is rarely a level surface. In fact the water table will always be inclined if water is percolating in a non-vertical direction from one portion of soil to another. For this reason, the water table in a hillside will tend to follow approximately the shape of the hill.

Because the word "table" usually refers to a flat surface, we prefer therefore to use a different term to describe the water table when it is inclined. We therefore use the term "phreatic surface". This water table, or phreatic surface will coincide with the water levels which are found in boreholes which are sunk to just below the phreatic surface. For example, in Figures 2, 3 and 4 the phreatic surfaces can be determined by small borehole tubes A, B, C, D and E. The phreatic surface through an earth dam is illustrated in Figure 2. Figure 3 shows the phreatic surface which exists between irrigation furrows on a hillside and a stream in the valley. In Figure 4 we notice that the phreatic surface in the immediate vicinity of a borehole is temporarily lowered because water is flowing through the soil towards the well. If the water table around the well were to remain level during pumping, then the significance of this impossible condition would be that no water was in fact percolating into the well from the soil.

It is generally true to state that water will only percolate into a freshly dug hole or depression if portion of this hole is lower than the adjacent water table or phreatic surface.

### The Coefficient of Permeability of a Soil

The coefficient of permeability is a term which is used to describe the ease with which water can percolate through a soil. The coefficient of permeability is usually determined in a laboratory test on the soil. However in certain cases it can be estimated by means of field pumping tests from boreholes.

The coarser the soil, the more easily water can percolate through the soil. The coefficient of permeability is therefore larger for coarse sandy soils than for fine-grained clayey soils.

Water can percolate one thousand times easier through a sand than through a clayey silt. And a pure clay offers even more resistance to flow than the clayey silt. In ascending order of magnitude of the coefficient of permeability, the main soil types can be listed as follows: clay, silt, sand, gravel and boulders. Note that this is also the order in which the grain size of the material increases.

Because the permeability depends on the grain size of the soil, one can also estimate the coefficient of permeability from the results of grain-size sieving tests. However, permeability tests are more accurate.

The author has described a simple test for determining the coefficient of permeability in section 5 of this paper.

### The Use of Flow Nets

A flow net is illustrated in Figure 5. This shows the flow pattern for water which is seeping through an earth dam. The curved lines which show the direction of seepage are called "flow lines". The region between two adjacent flow lines is a "flow path". The curved lines which cross the flow lines at right angles are "equipotential lines".

This particular flow net has been drawn for a two-dimensional flow system. In other words all the water flow is in the plane of the paper, and no water is flowing at right angles to the plane of the paper.

A flow net is drawn by trial and error until the correct flow net is obtained. Certain requirements must be satisfied for the flow net to be correct. These are as follows:

(*a*) If the horizontal and vertical permeabilities are identical in value then the equipotential lines and flow lines must intersect each other at right angles.

(*b*) Two different flow lines may not meet or intersect each other.

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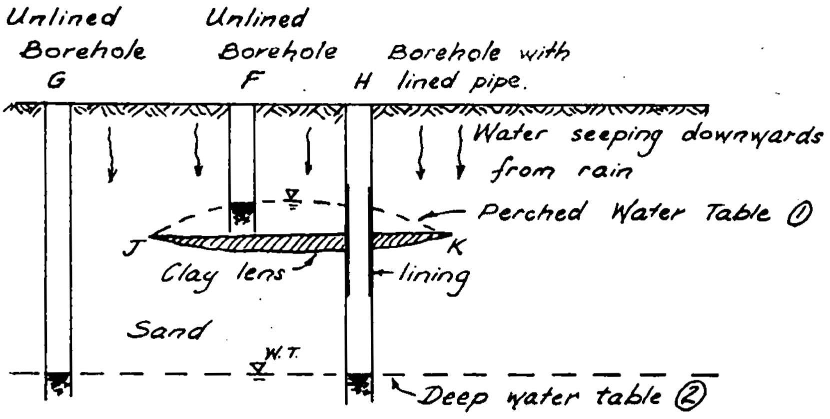
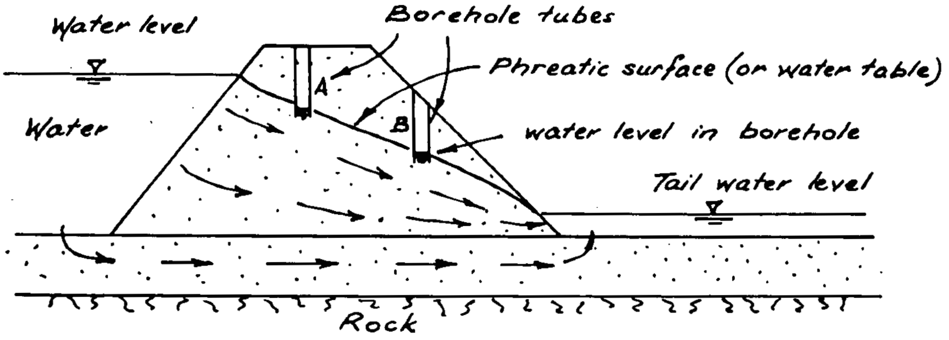
* This paper was received too late to be read and discussed at the Congress.



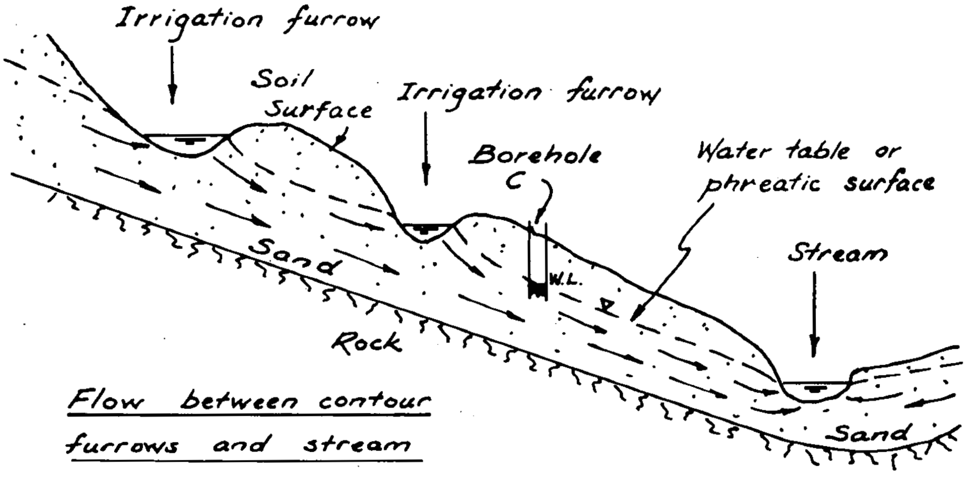
Two types of water tables.

Figure 1



Seepage through dam

Figure 2.



Flow between contour furrows and stream

Figure 3.

(*c*) Except in the region of a sharp impervious point, two different equipotential lines may not appear to touch each other.

(*d*) The points at which the equipotential lines meet the phreatic surface must be situated at certain horizontal levels. These horizontal levels must all be spaced at the same vertical distance *y* apart. For this reason the vertical height difference between the water level in the dam and the tail-water level must be divided into a number of vertical divisions each being equal to the same distance *y*.

One may choose any convenient number of subdivisions of the distance H. Let the number of equipotential subdivisions be N*d*. In Figure 5, the value of N*d* is 8.

(*e*) The main requirement for the flow net is that the equipotential lines and flow lines must form a system of "curvilinear squares". A curvilinear square *cdef* is illustrated in Figure 6. If the "square" is further subdivided by lines X-X and Y-Y then figures which look like true squares will eventually result.

The number of flow paths should be counted. In Figure 5 the number of flow paths N*f* is 2.5.

Two people will seldom draw identical flow nets for a particular dam section, because they will probably start with different values of N*d*. This will also mean that their values for the number of flow paths N*f* will not be the same. However if they have both drawn their flow nets correctly they will both obtain the same value for the ratio N*f*/N*d*.

(*f*) Certain other requirements must also be met. For example, equipotential lines must meet impervious boundaries at right angles (e.g. the equipotential lines in Figure 5 meet the impervious rock at right angles).

Flow lines should also meet a free body of water at right angles. (e.g. In Figure 5, the flow lines meet the upstream surface of the dam at right angles).

However, if a flow line or an equipotential line meets the downstream face of a slope above the downstream free body of water, then this means that the water comes out on to the slope and then flows freely as a stream down to the tail water level. If a flow line comes out of the slope above the tailwater level then this flow line does not necessarily intersect the slope at a right angle.

The flow net can be used to estimate the seepage loss of water through the earth dam.

If we consider a one foot wide strip of the dam (i.e. one foot measured at right angles to the plane of the paper in Figure 5) the seepage loss through this one foot wide section is

$$Q_1 = k_1 H . Nf/Nd \text{ (cubic feet per second per foot width of dam)} \quad (1)$$

where $k_1$ = coefficient of permeability of the soil (ft/sec).

H = difference in water level in feet (see Fig. 5).

N*f* = the number of flow paths (=2.5, in Fig. 5).

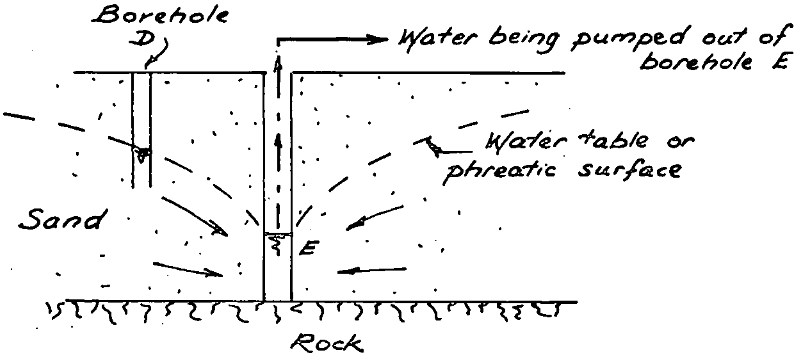
N*d* = the number of equipotential drops (= 8, in Fig. 5).

In order to calculate the seepage loss through the whole dam (cubic feet per second) we must multiply the value of $Q_1$ found from equation (1) by the total width of the dam across the valley (where the total width is measured in feet).

### A Simple Permeability Test

It is reasonable to suppose that a farmer will not be prepared to devote considerable time to the study of flow nets. He is merely interested in knowing whether his proposed dam will suffer from a leakage of approximately 10 gallons a day or 10,000 gallons per day.

In this section, and the next section, a simplified method will be given for estimating the approximate rate of seepage from the proposed dam.



3-Dimensional flow into borehole

Figure 4.

The author suggests that the following method may be used for calculating the coefficient of permeability.

(*a*) Take any large diameter pipe which is approximately 6 ft. 6 in. in length. A suitable diameter for such a pipe is 6 inches diameter or larger.

(*b*) Place the lower end of the pipe on two or three bricks as in Figure 7, and support the pipe in a vertical position by tying the pipe to a fence stake.

(*c*) Fill up the spaces between the bricks by using coarse gravel and small stones. Pour coarse gravel around the bottom of the tube and the bricks. Place approximately 3 inches of coarse stone inside the bottom of the tube. Then pour in approximately a three inch depth of coarse sand (see Figure 8).

(*d*) Cut two circles of hessian sacking. These should be just larger in size than the inside dimension of the pipe. The fairly open weave used for potato pockets or wool bales should be suitable. (Do not use large open weave material which is used for orange bags as this will permit the loss of fine grained soil through the open weave.)

The two circles of hessian are placed centrally on the coarse sand. This can be done with a long stick. A mirror may be used to reflect sunlight down the tube. The top of the tube should be at least 5 ft. 6 in. above the hessian.

(*e*) The soil which is to be tested should be dried (in an oven if necessary) and all lumps should be broken down. Clay should be ground into a dried powder.

(*f*) Measure the exact distance from the top of the tube to the level of the hessian. Make a mark in the tube 5 ft. 6 in. above the hessian.

(*g*) Pour the dry soil on top of the sacking and compact the soil with the end of a wooden plank. The final level B of the dry soil should be exactly 1 ft. above the level of the hessian (see Figure 8).

(*h*) Place a few inches of coarse stone on top of the soil.

(*i*) Pour water into the tube until the water level is at C which is 5 ft. 6 in. above the hessian.

(*j*) Wait for a while until the water has saturated the dry soil. In the case of a sandy material one can wait until the water begins to run out at the bottom of the tube. In the case of a clay one should wait for about one day.

(*k*) As the soil is now saturated we can top up the water level again to the level C and start the test.

(*l*) Determine the time in minutes for the water level to fall one foot from the level C to the level D (see Figure 8). For coarse sands this time will be approximately 10 minutes to 100 minutes. In the case of clays it will take many days for this water level to fall one foot. If the test is likely to take

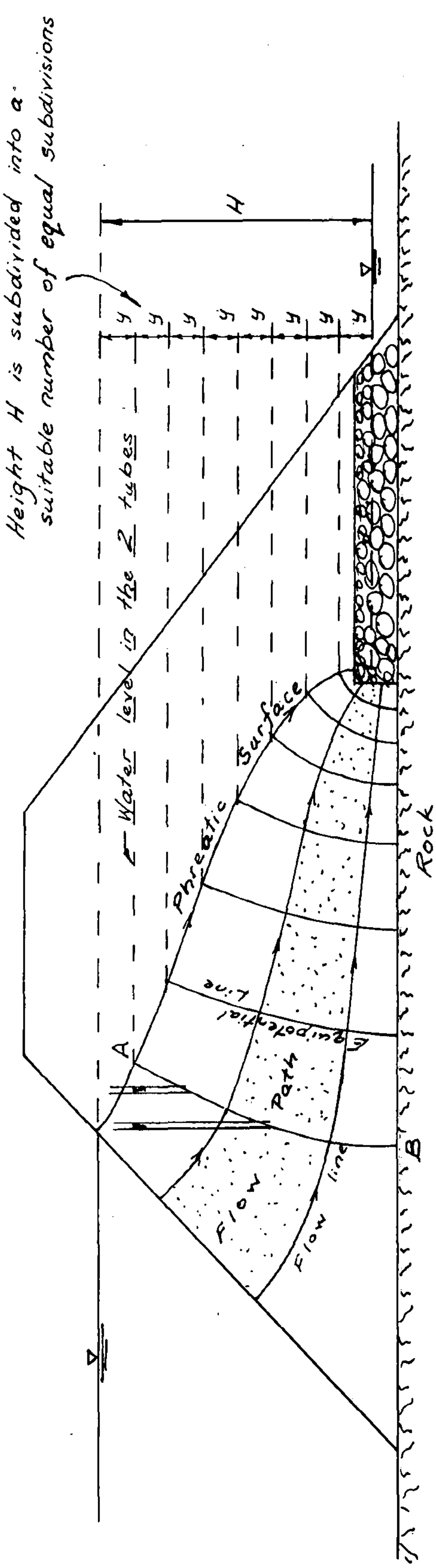


Figure 5

Flow Net for an Earth Dam

In this flow net, number of flow paths $N_f = 2.5$, number of equipotential divisions $N_d = 8.0$

a long time one should cover the top of the tube with a plastic fertilizer bag which is tied on to the tube to prevent rain from entering the tube.

In the case of clays the test can be expedited by merely measuring the time required for the water to fall one inch. One can then estimate the time in minutes which would be required for the water level to fall 1 foot (1 day = 24 hours = 1,440 minutes).

The coefficient of permeability $k$ can be calculated from the formula

$$k = \frac{1}{10 \times t} \text{ (centimetres per second)} \qquad (2)$$

where $t$ = time in minutes for the water level to fall one foot from level C to level D.

A coarse sand may have a value from 0.01 to 0.001 (i.e. $10^{-2}$ to $10^{-3}$) cm/sec

A clay may even have a value as low as 0.000001 (i.e. $10^{-6}$) cm/sec

A silty soil will have a value intermediate between the clay and the sand values.

### To Estimate the Approximate Seepage from the Dam

When drawing the flow nets for dams one finds that the value of N$f$/N$d$ seldom exceeds 0.6 or 0.7. This value of N$f$/N$d$ can therefore be used to find a conservative or safe value for the estimated seepage through the proposed earth dam.

The following formula should give a conservative or safe estimate of the seepage through the proposed earth dam:

$$\text{Total seepage through whole dam} = Q = (D + 10) \,.\, H \,.\, k \,.\, 12{,}000 \text{ (gal. per day).} \qquad (3)$$

$$\text{or } Q = (D + 10) \,.\, H \,.\, k \,.\, 2{,}000 \text{ (cubic ft. per day)} \qquad (4)$$

where D = the dam length across the valley measured in feet.

H = the maximum height difference in feet between the water level in the dam and the stream water level at the tailwater side of the dam.

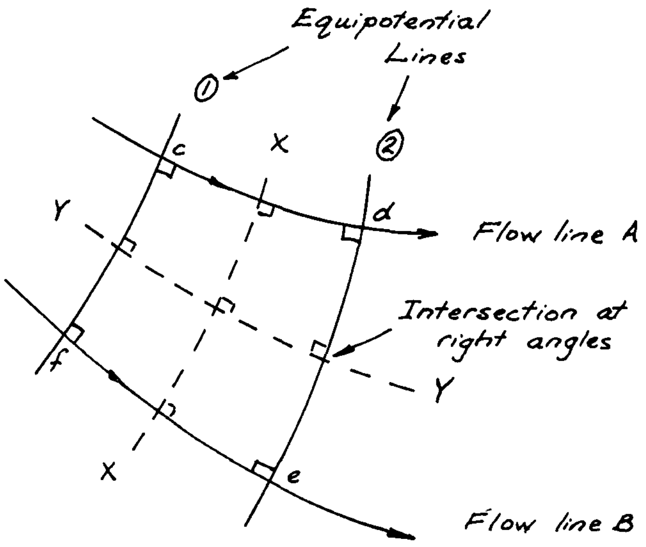
$k$ = the coefficient of permeability of the dam material as found from equation (2) (measured as cm per sec).

When using equations (3) or (4) one is assuming that the entire dam and its base are constructed from the material which was tested to find the value of $k$.

The rate at which the water level in the dam will fall due to seepage losses can be estimated as follows:

Estimate the anticipated maximum surface area of the water in the dam when the dam will be full. Let this be A square feet.

Calculate the value of Q from equation (4). Divide the value of A into this value of Q to find an answer which is equal to the distance in feet which the water surface will drop each day. Multiply your answer by 12 to obtain your answer in inches.



A "curvilinear square" cdef

When subdivided by lines XX and YY the "square" cdef yields further squares.

Figure 6.

This calculation obviously does not make an allowance for losses due to evaporation from the water surface in the dam.

## Special Flow Net Problems

Flow nets can be drawn or calculated by electronic computer for complicated problems such as the problem in Figure 3 or three-dimensional flow problems such as in Figure 4.

The author has also developed a graphical method for drawing the flow nets for three dimensional flow. This is based upon the principle that one can still draw curvilinear squares for certain three-dimensional flow nets provided the equipotential lines do not meet the phreatic surface at equal vertical intervals.

The effects of soil layering can also be taken into account in the drawing of flow nets. It is interesting to note that a flow line is refracted at the interface between one soil type and another. This is somewhat similar to the bending of light rays which pass from air into water.

Although various electrical methods exist for analysing flow nets, the author has found that the drawing method is much quicker than the electrical methods and it is also quicker to apply than certain other analogies which are available.

The author has also applied the flow net principles to estimate the flow capacity of certain septic tank systems.

## Flow above the Water Table

Flow of water can occur above the water table as shown in Figure 9. A ditch has been provided with an impervious polythene lining such that the upper edges of the polythene are above the water level AB in the ditch. However, due to syphonic and capillary action the soil can act as a syphon and transfer water from the ditch to the surrounding soil.

In order to cut off the syphon action the polythene sheet should be turned back to the sides of the ditch as shown in Figure 10.

The analysis of water flow above the water table is usually analysed by considering the suction pressures (or $pF$ values) of the soil.

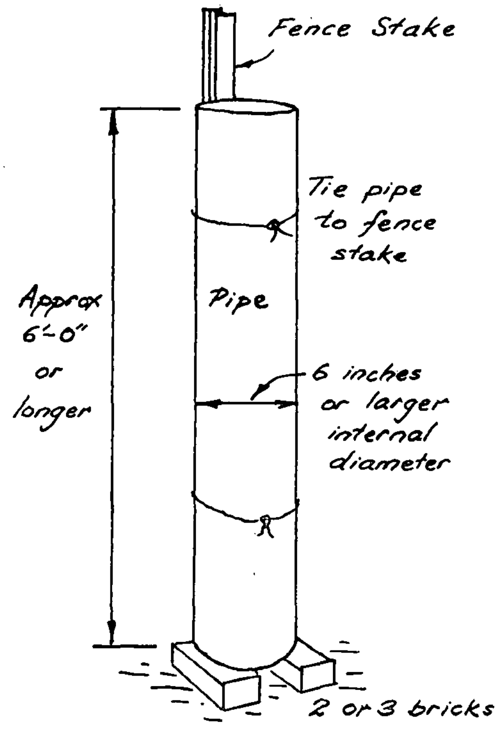
If a sample of soil is at a height of $h$ centimetres above the water table and if equilibrium has been reached, then the water pressure in this element of soil will be less than atmospheric pressure by a pressure difference equal to the height $h$ of water. The $pF$ of the soil is a measure of this pressure suction and can be found by the formula

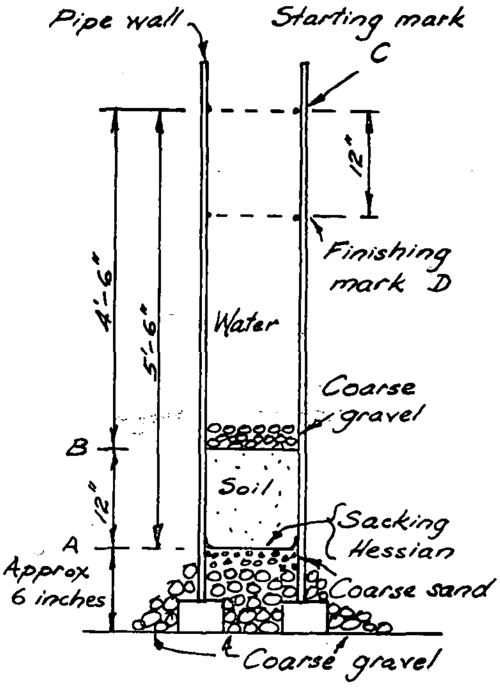
$$pF = \log_{10} h \text{ where } h \text{ is measured in centimetres.}$$

If two elements of soil are at the same horizontal level, moisture will move from the sample of low suction (low $pF$) to the element of higher suction (high $pF$).

Temperature also affects the $pF$ values and the water vapour pressure within the soil. Consequently we find that moisture moves from a warm region to a cold region within the soil.

Plants wilt when the $pF$ value of the soil becomes too large. When the $pF$ value of the soil becomes too





Simple permeability test.

Figure 7. Figure 8.

large, the plant roots find difficulty in removing moisture from the soil.

The *p*F of a soil can be determined by measuring the electrical conductivity of plaster of paris blocks which are buried in the soil. As the *p*F of the soil decreases, the conductivity of the plaster of paris increases.

Buried plaster of paris blocks can therefore be used to determine the effectiveness of spray irrigation systems. Much research has been done on the classification of soils in various agricultural regions. The author believes that a useful survey could be made by burying thousands of plaster of paris blocks throughout the country. Soil maps could then be made of the average *p*F values of the soils during the four seasons of the year.

Due to lack of space, further particulars relating to the use of *p*F measurements might be given in a future paper.

### Conclusion and Misconceptions

In conclusion the author wishes to draw attention to certain popular misconceptions which exist.

(*a*) A clay is always more moist than a sand from the same region. This does not mean that a clay conducts water more easily than a sand. It merely means that the clay is more reluctant than a sand to impart its moisture to the atmosphere by evaporation.

(*b*) The height of capillary rise of moisture from the water table is not limited to about 35 ft. Capillary rises can occur to much greater heights. The finer the size of the soil grain, the higher the possible capillary rise.

(*c*) Water does not always flow from a region of high pressure to a region of low pressure. For example in Figure 2 water is made to flow down an inclined tube AB from A to B. The water height above A is smaller than the water height above B. In other words the water pressure at A is less than the water pressure at B yet the water must obviously flow from A to B because the water level on the left is higher than the water level in the tube at the right.

The equipotential lines in Figure 5 should therefore not be regarded as equal pressure lines. The water pressure actually varies along an equipotential line. If we place tubes down to the equipotential line AB in Figure 5 we will find that the water levels in all these tubes will be at the same level.

Water actually flows from a region of high potential level to a region of low potential level. We can only state that water will flow from a region of high pressure to a region of low pressure if the water is flowing horizontally. In other words we should always take into account the difference in level between the two points A and B.

(*d*) Similarly we should not state that water will always move from a region of low *p*F to a region of high *p*F. It will only move from a region of low *p*F to a region of high *p*F if the difference in *p*F values is such that this difference is greater than the pressure corresponding to the height difference between the two regions.

(*e*) Water will not always move from a soil of high water content to a soil of low water content. For example a clay with a high water content can be adjacent to a sand with a low water content and yet moisture may be moving from the sand to

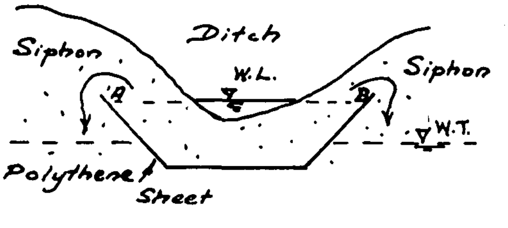


Figure 9

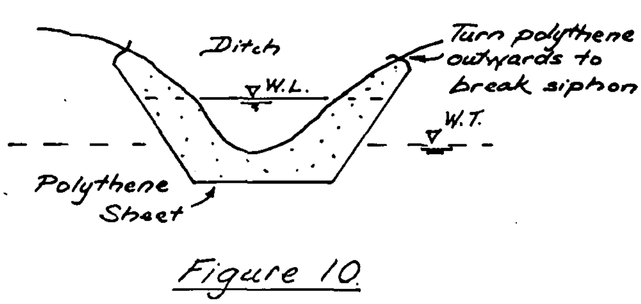


Figure 10

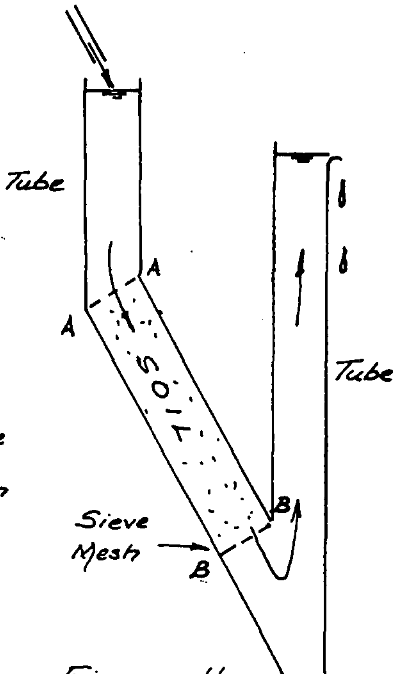


Figure 11

the clay because the *p*F value of the clay is higher than that of the sand (water content is defined as "weight of water divided by the dry weight of the solid grains"). Movement of water above the water table does not therefore depend upon differences in water content, but differences in the *p*F values between the various regions and the height differences between these regions. Below the water table the water movement is determined by the positions of the equipotential lines.

### References

(1) Terzaghi and Peck, Soil Mechanics in Engineering Practice, Wiley, 1948.

(2) Sparks, A. D. W., Various Aspects of Soil Moisture, 3rd African Conference on Soil Mechanics and Foundation Engineering, c/o Rhodesian Institute of Engineers, Salisbury, 1963.

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The Chairman, Mr. J. L. du Toit, closed the day's proceedings with the following remarks:

**Mr. du Toit:** We have come to the end of today's proceedings and I wish to thank all you experts for your papers and for your contributions to the interesting discussions which have ensued.

On your behalf I want to pay a special word of thanks to Dr. B. E. Beater for all the work he has done. He organised this soil science session, but apart from presenting one paper he has kept himself in the background. We tend to take him for granted. Dr. Beater has spent many years in soil research at the Experiment Station, and I feel today is in some respects a crowning day for him.

We have in this room a collection of soil monoliths which is probably unique in South Africa, and probably as good as any in the world, and this is due to Dr. Beater. The method of preserving these monoliths is his and the soil series they represent are also the results of his research. He has done pioneering work in soil science in the sugar belt and in fact in South Africa, and has many scientific publications to his credit. I feel we are indebted to him, not only for his research, but also for enabling us to hold this very successful soil science session today. (Applause).