A FIELD METHOD FOR MEASURING THE PERMEABILITY OF SOIL BELOW A WATER TABLE[1]

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SYNOPSIS

The measurement of water permeability of soil under field conditions is a problem of major importance in connection with the design of structures for controlling ground water. Present methods of permeability measurement are not entirely satisfactory, particularly with respect to the measurement of permeability when it is desired that the natural field structure not be disturbed and that the readings be statistically significant. This paper presents a method of permeability measurement, in the field, below the water table, involving a minimum of soil disturbance and yielding statistically significant results.

The method involves the insertion of a tube into the soil to the depth where the measurement is desired, the removal of the soil from the tube, the emptying of the water in the tube to a known distance below the water table level, and the measuring of rise of water in the tube in a known time. The permeability is determined in standard units using a formula based on Darcy's Law. The formula involves the radius of the tube, the depth of the tube below the water table, and a certain constant obtained in the laboratory. The constant, evaluated in the laboratory, depends upon the radius and depth of the tube. It was determined by a three dimensional electric analogue of its ground water flow system, the ground water flow having been simulated by a corresponding electric current flow. The analogue was also used to obtain the streamline pattern, and lines of equal hydraulic head, and to evaluate changes in the rate of flow due to obstructions, such as rocks, which may be near the end of a tube. The analogue was used because a mathematical analysis of the problem is not at hand. The effect of rocks and other obstructions on the accuracy of the measurements was found to be small.

The field equipment consists of apparatus for driving the tubes quickly, for removing the soil from the tubes without puddling the exposed soil surface, for measuring the water levels, and for pulling the tubes from the soil. Eight inch diameter tubes were used in this study.

Some field data are also reported in this paper. Statistical methods were used to determine, from the data, the number of tubes required to obtain measurements of a reasonable degree of accuracy. The results indicate that permeability determinations at depths of 6 in. or less are difficult to duplicate and are of doubtful value. At depths of 12 in. or more, satisfactorily uniform results were obtained.

Two additional methods of permeability measurement are briefly described. The first, a modification of the above method, involves driving tubes 1 in. in diameter into the soil, and removing the soil to a depth 4 in. below the tube with a conventional soil auger. The second method measures permeability by observing the rate at which a hole, dug with a post hole auger, fills with water. In both the latter methods the electric analogue was used to obtain factors to convert measured values to standard permeability units.

When soil is used as an engineering material it is often necessary to obtain information on the resistance of the soil to the flow of water through it. This is especially true when the soil is used as a fill material to form a dam. However, if the soil is so wet that it will not provide a stable foundation for a building, a

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[1] A joint contribution of the Soils Sub-section and the Agricultural Engineering Section of the Iowa Agricultural Experiment Station, Journal Paper No. J-1650, Project 998. Some of this material was presented to the annual meeting of the American Society of Agricultural Engineers at Portland, Oregon in June 1948.

road, an airport landing strip, or is so waterlogged that it will not support crop growth, the characteristics of the soil which relate to water movement again become important.

While investigators have given considerable attention to problems dealing with the flow of homogenous fluids through porous media, there is still no complete agreement on the definition of the terms relating to the rate of movement of water in soil. Most investigators have characterized the ability of the soil to transmit water as its permeability. Muskat (*10*)[2] defined permeability as "... the volume of a fluid of unit viscosity passing through a unit cross section of the medium in unit time under the action of unit pressure gradient ...." Muskat suggested, however, the use of an effective permeability for cases where gravity is the only driving agent and where the liquid is water. In this event the permeability unit may be expressed as the quantity of water passing in unit time through a unit cross section under a unit hydraulic gradient.

Infiltration and percolation are sometimes confused with permeability. Baver (*1*) has attempted to make the distinction clear by defining infiltration as "... that process whereby the water enters the environment of the soil through the immediate surface", and by referring to percolation as the "... movement of water through the profile. ...." According to Baver's concept, the percolation through a unit area in a unit time is numerically equal to the soil permeability as given in the second definition above. This is true because when water moves steadily downward, with the soil friction balancing the force of gravity, the water is subject to a unit hydraulic gradient.

Permeability data are particularly needed in the design of sub-surface drainage systems. It is basic that the speed with which water moves to a tile drain is directly proportional to the soil permeability. The optimum spacing and depth of tile systems are therefore directly dependent upon the permeability of the soil in which they are placed. Just how the permeability is tied in with the spacing, depth, size, etc. of drains is not known, except in some special cases such as those worked out by Kirkham (*9*) and Childs (*2*). When a general relationship of all these factors is obtained, a rational approach to the problem of designing drainage systems will be available. One possible method of determining this relationship is based upon analytical study, another on field observations of experimental tile drainage systems, still another, the use of either sand or electric models. A number of investigators are working on this problem and there is good reason to expect that the relationships connecting soil permeability to depth, spacing, etc. of drains will be established in the foreseeable future.

There are a number of standard methods of making permeability measurements. Some of these involve the placing of loose soil in a container, tamping to a predetermined degree, applying a head of water, and measuring the rate of flow of water through the soil material. Others involve the removal of "undisturbed" samples from the soil, the application of a head of water and a similar determination of the flow rate. While these methods have presented much valuable and useful data, they have all been limited by the difficulty of duplication of data, or in other words, by the accuracy with which the measurements could be made. Factors such as the variability of the soil and the formation of air pockets in the unsaturated zones of the profile as well as the lack of standardized procedures have been largely responsible for these difficulties. Variation in measurements up to and exceeding 1000 percent are not uncommon (*3*).

OUTLINE OF PROCEDURE

In the present paper a procedure is described for measuring the permeability of the soil, in place, below the water table, which obviates a number of the difficulties indicated above. The general plan followed is that suggested by Kirkham (*8*) for the field measurement of soil permeability. His proposal is based on Darcy's Law. Kirkham suggested that a cylindrical pipe be placed tightly in a hole of the same size and filled with water to a measured height above the water table. The fall in the water level in a given time was then to be observed and the permeability determined by the use of the formula:

$$K = \frac{\pi R^2 \ln (h_1/h_2)}{A(t_2 - t_1)} \qquad [1]$$

where,

K = permeability in inches per hour for unit hydraulic gradient

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[2] Italicized figures in parentheses refer to the list of references at the end of the paper.

ln = natural logarithm (base e)
h_1 = distance of water level in tube from water table at time t_1
h_2 = distance of water level in tube from water table at time t_2
R = radius of tube in inches
$t_2 - t_1$ = time for water level to change from h_1 to h_2 in hours
A = a coefficient determined by the use of an electric analogue.

The method described here and reported by Frevert (*4*), differs from that proposed by Kirkham in that instead of pouring water into the tube to create a higher hydraulic head inside than out, water is removed from the cylinder so that the soil water moves in. This modification is important from a practical point of view, the theory being the same in either case. Figure 1 shows the field dimensions used in these permeability determinations.

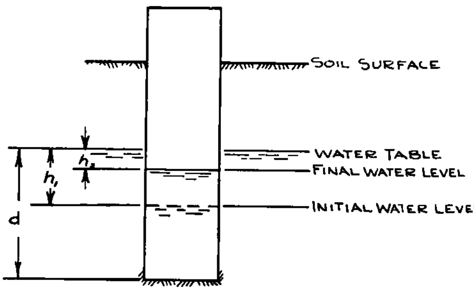

Figure 1. Field Dimensions for Determination of Permeability

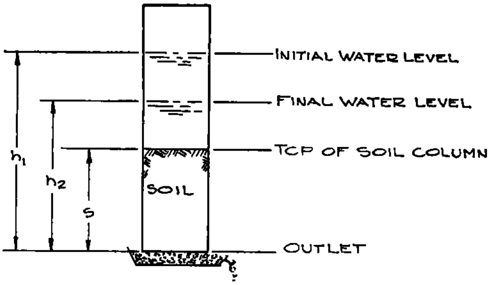

Figure 2. A Common Type of Permeameter

In equation [1] all the quantities can be readily obtained with the exception of the constant A. This constant (the A-function) is a function of the diameter of the tube, of the ratio of the depth to the diameter of the tube, and of the shape of the soil surface at the end of the tube. The A-function is a constant for a given geometry. The physical significance of the A-function is that it takes into account the flow pattern of the water in the soil. In some simple cases of flow in porous media, A-functions can be computed analytically. For example, when water flows rectilinearly, as in the common type of permeameter shown in Figure 2, the permeability formula is

$$K = s\frac{\ln (h_1/h_2)}{t_2 - t_1} \qquad [2]$$

Comparing this with equation [1], it is evident that the A-function for this permeameter is simply $\frac{\pi R^2}{s}$. When water moves into or out from a spherical cavity at considerable depth below a water table, the A-function as shown by Kirkham (*8*) is

$$A = 4\pi r_w \qquad [3]$$

where r_w is the radius of the sphere. The A-function always has the dimensions of length.

Experimental work in this study was conducted both in the laboratory and the field. Laboratory experimentation as pointed out previously, was necessary to evaluate the A-function, to investigate the effect of obstructions in the region of measurement, and to determine the flow net. The field study consisted of a preliminary investigation of the problems involved, the design and construction of necessary equipment, the development of an operative procedure, and the taking of field data.

In reducing the field data to permeability units, the results are expressed in inches per hour at unit hydraulic gradient. As suggested by Gustafsson (*5*) and other investigators, the permeability was corrected for viscosity as affected by the temperature of the percolate. Permeability results were corrected to that of water at 20.2 deg. C.

ELECTRIC ANALOGUE

While the A-function, as pointed out by Kirkham (*8*), can be evaluated by use of a sand tank model, by analytical methods, or by an electric analogue, the last was selected because it was felt that the equipment would be more flexible, would provide the data in a shorter time, and would be generally more satisfactory. Although electric analogues have been used with solid materials, it was decided here to utilize a liquid conductor because probe measurements could then be more easily made.

In constructing the analogue, a wood tank 6 ft. in diameter and about 20 in. deep was utilized. The tank was fitted with an inside copper bottom. This bottom served as one electrode in the analogue, representing the top of the water table in the field. The second electrode in the laboratory model was the copper end of a rod whose sides were coated with an insulating paint (glyptol). This rod was the equivalent of the field tube. The conducting end of the rod represented the soil water interface at the bottom of the field tube; the insulated sides of the rod represented the impervious walls of the field tube. The rods were in lengths of $\frac{1}{2}$, 1, 2, and 4 in. with diameters of $\frac{1}{4}$, $\frac{1}{2}$, and 1 in.[3] The water surface in the tank was comparable to an impervious layer below the soil surface.

The conductivity of the fluid was determined by the use of a modified graduate filled with the electrolyte and containing two parallel copper disks spaced so as to make possible the evaluation of resistance between the plates. The device used for measuring resistance was a Bouyoucos bridge as used in standard soil moisture measurements. This unit was not very sensitive at low resistances and is now replaced by more suitable equipment.

The determination of the constant A was carried out for each of the electrodes. The applicable formula is

$$A = \frac{R}{R_m \sigma \omega} \qquad [4]$$

where,

R = radius of tube

R_m = radius of model

σ = specific conductivity of electrolyte

ω = resistance between electrode and tank bottom

Here ω replaces $\frac{V_2 - V_1}{I}$ as given in Kirkham's (*8*) equation for this determination.

The data were taken and applied and plotted as shown in Figure 3. The curve fitted to the data, according to the method of least squares. This gave the relationship $Y = 21.0 - 0.117\,X$, when Y is the numerical value of A for a tube of 8 in. diameter, and X is the ratio of depth below the water table to tube diameter. A secondary abscissa is included to facilitate obtaining values of the A-function for tubes other than 8 in. in diameter. The dashed lines indicate the manner of determining the A-function when the ratio of depth to diameter is 5 and when a 6-in. diameter tube is to be used. The resulting constant is found to be 15.3.

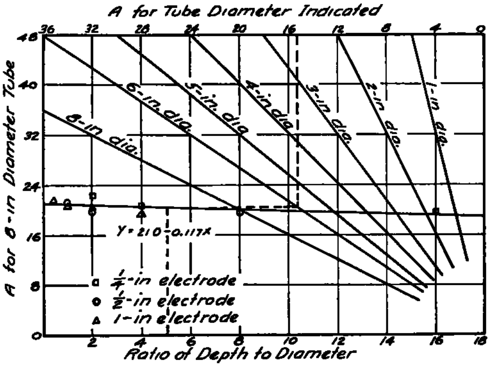

Figure 3. Values of A-function

Studies were made to determine the effect of an obstruction below the tube and to evaluate the effect of the nearness of a possible hard-pan layer to the bottom of the tube. It became evident that permeability measurement will not be seriously affected unless an obstruction covers over one-fourth of the tube end or unless an impervious layer is within about one diameter from the end of the tube. It was also shown that surface disturbance caused by standing near the tube would have a very small effect on the rate of flow from the end of the electrode to the copper bottom of the tank.

A special device for recording equipotential lines was constructed as shown in Figure 4. The approximate streamlines were located, as shown in Figure 5, with the aid of an inverted electric analogue (*4* and *11*).

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[3] Another set of electrodes was constructed and data taken for the case in which the soil is not removed from the tube. In view of a very considerable reduction in permeability due to compression of the soil inside the tube, this method is not recommended.

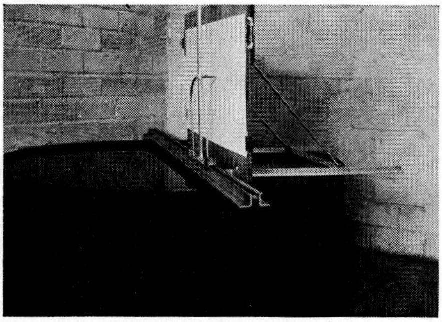

Figure 4. Device to Record Lines of Equal Hydraulic Head and Streamlines

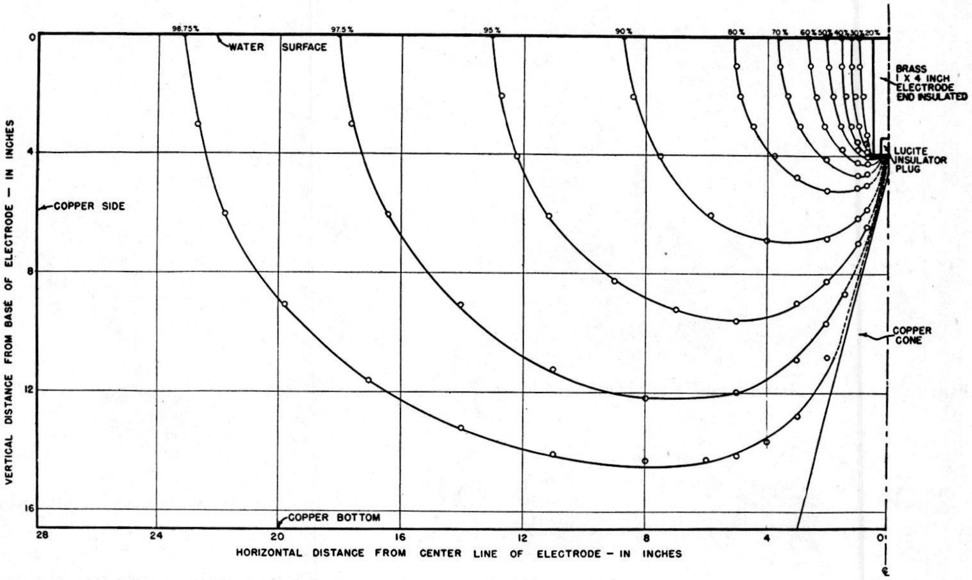

Figure 5. Streamline Pattern as Located by Inverted Electric Analogue, the Copper Cone Simulating a Limiting Equipotential.

The theoretical value of the A-function for a spherical electrode was calculated using equation [3]. While the field situation corresponding to use of a spherical electrode was not realized, this calculation did provide a check between the theoretical and measured values of the A-function. The variation between these values was less than 2 percent and the validity of the procedure was considered substantiated.

FIELD STUDIES

Equipment

The equipment was designed and constructed in accordance with the results of a series of preliminary observations. The basic pieces of field equipment were the tubes, a driver to insert the tubes, soil removers to empty the tubes, water level measuring devices, and a puller for removing the tubes.

The tubes were constructed of 20-gage galvanized sheet steel. Flanges were formed on the edges to be joined and the seams were fusion welded with an acetylene torch. The finished cylinders were 30 in. long and 8 in. in diameter. The bottom edge of the tube was sharpened on the outside to facilitate driving and to minimize the compression of the soil inside. Soldered tubes, as first used, proved too weak to withstand pounding.

The driver is pictured in Figure 6. The head of the driver was formed of a cylindrical section of steel. The lower portion of the head was machined to fit into the tube. A guide rod was welded into the center of the head in a line concentric with the tube. The guide rod helped to drive the tube straight. A cylindrical 24-lb. weight with a hole drilled through its axis served as the hammer, being free to slide up and down on the guide rod. A reinforcing clamp fitted over the outside of the tube prevented the top of the cylinder from being deformed. An annular masonite disk, $\frac{1}{4}$ in. thick, was placed over the guide between the hammer and the head to cushion the impact of the hammer. Figure 7 shows the equipment in use in a ponded area.

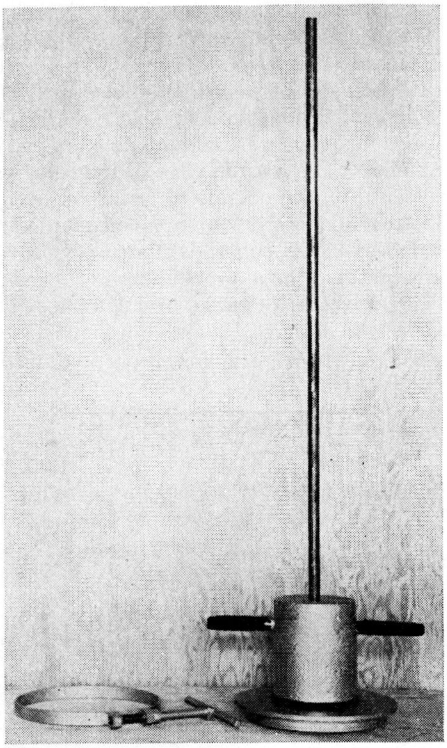

Figure 6. Tube Driver and Reinforcing Clamp

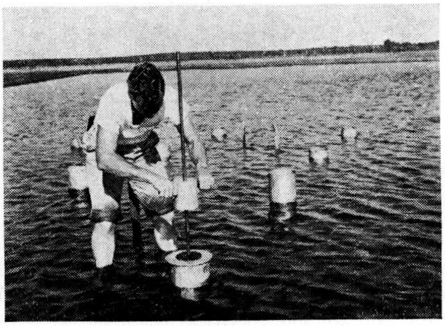

Figure 7. Driving Tubes

As available equipment proved unsatisfactory for the removal of the soil from the inside of the tube, it became necessary to construct a special soil removing device. As shown on the right-hand side of Figure 8, the device consisted essentially of a welded steel rim with four vanes connected into the hollow center pipe. The handle was welded on to the end. The hole in the center rod allowed the air to enter below the apparatus, breaking the vacuum and allowing easier removal of the soil. In some cases it proved desirable to insert a probe through the hollow center rod to keep the opening from clogging with mud. The angle of the vane kept the soil from falling off. As the handle was turned only enough to hold the soil on the blades, a shearing action on the soil at the bottom was avoided. A simultaneous lifting action broke the soil in tension. This procedure minimized the disturbance of the soil structure.

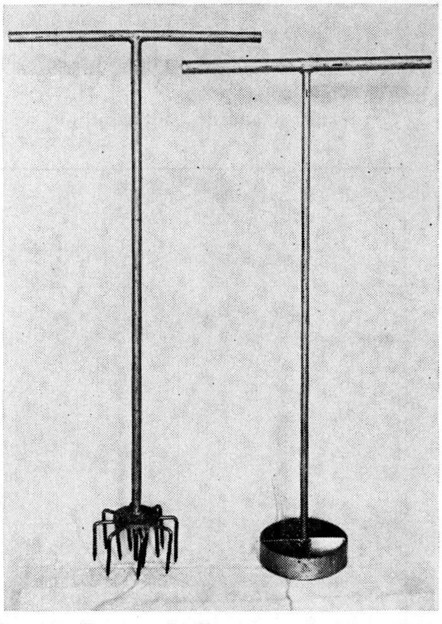

Figure 8. Devices for Removing Soil from Tubes

While the vane worked satisfactorily near the surface in some soft soils, it still proved unadaptable to a wide variety of situations. Another piece of removal equipment was constructed, in which the rim was omitted and use was made of claw-like rods instead of vanes, as shown at the left of Figure 8. Although in some cases the soil slid from the rods and had to be removed by hand, this device performed more satisfactorily than the former one.

The tube puller consisted of an oak block $3\frac{1}{2}$ in. thick which was divided into two pieces through the center. In order to keep the two pieces in proper alignment, three $\frac{5}{16}$-in. metal pins were set into one-half of the block and corresponding holes were bored into the other half. Two metal wedges were then constructed and fastened to a handle as shown in Figure 9. The wedges fitted into the slot between the blocks in such a way that when the handle was lifted the blocks would be separated to give a friction grip on the inside of the tube. After the tube was removed, a downward push on the handle released the wedges. A short section of chain fastened to one block could be placed over the handle and hooked to the other block, making possible the removal of the puller from the cylinder. Whenever the water table was at or above the water surface, two men using the puller were able to remove the tube.

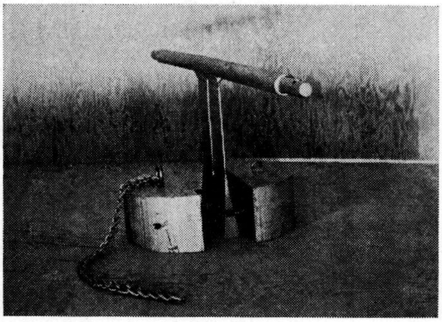

Figure 9. Device for Removing Tubes from Soil

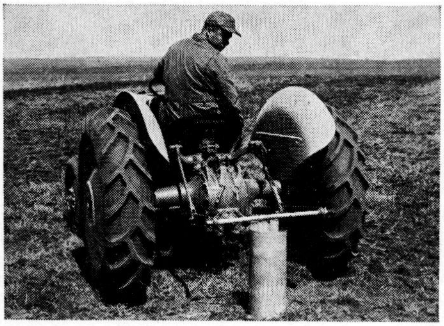

Figure 10. Pulling Tube by Tractor Power

In one situation, where measurements were made when the water table was below the surface, the tubes were removed by attaching the puller to the lift arms of a Ferguson linkage of a Ford tractor, as illustrated in Figure 10. While the tubes were lifted in this way without difficulty, some slippage in the release valve indicated that the capacity of the lift system had been reached.

The water table level was measured with a modified triangular engineer scale, which could be read to the nearest 0.01 in.

Field Procedure

The procedure followed in the field studies is diagrammed in Figure 11, which shows the situation at three depths of measurement. The permeability measurements were made in locations considered to be typical of the area in question. It was important that the soil should not have been unduly agitated or puddled and that the tubes were placed where there was no evidence of disturbance of the soil. The tubes were placed 6 ft. apart to form an array of rectangles. This distance of 6 ft. was selected after considering the concentration of stream lines near the tube as shown in Figure 5.

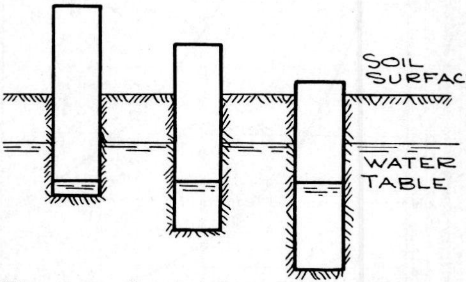

Figure 11. Sequence of Tube Positions for Permeability Measurements

Readings were taken with water flowing into the tube. By careful adjustment of the water level, the initial head between the outside and the inside of the tube was made the same for each run. This difference was usually 6 in. The time interval selected was about the same as that required to reduce the initial difference approximately one-half. Readings taken after the water levels had nearly reached equilibrium would not be of much value, because the rate of water movement would then be very slow. After the permeability readings had been taken, determinations of soil water temperatures were also made for each depth. A thermometer placed in the soil at the bottom of the tube gave the temperature.

The permeability values were calculated by the use of equation [1], after the value of the required A-function had been taken from Figure 3. These permeability values were corrected by means of the graph in Figure 12 for viscosity changes caused by variations in temperature. This graph was based on data determined by Bingham and Jackson in the *Handbook of Chemistry and Physics* (*6*). They report that the viscosity of water at 20.2 deg. C. is one centipoise. The permeability as presented in Kirkham's equation is inversely proportional to the viscosity. Therefore the factor to correct the calculated permeability to that of soil with water at 20.2 deg. C. and the numerical value of the viscosity of the water in centipoise are the same. The graph makes use of this fact.

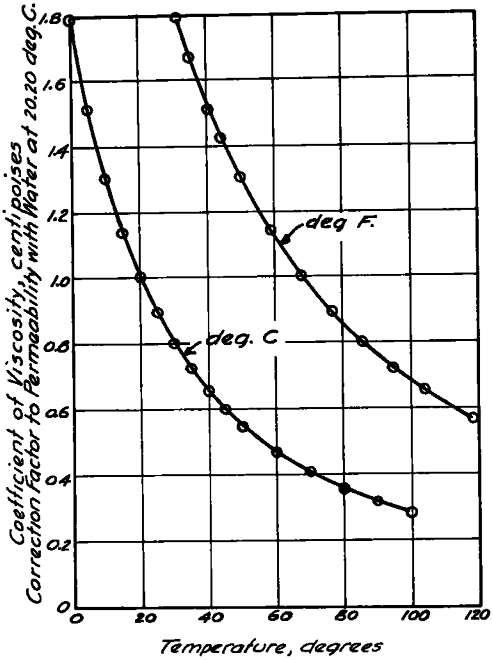

Figure 12. Factor to Correct Permeability to Temperature of 20.2° Centigrade

Results

The results of one of the several field trials are given in Table 1. Arithmetic means and standard deviations were calculated for the various runs in accordance with the usual procedure. The principle of fiducial limits was applied to the data to determine the number of tubes which would be required so that the permeability obtained would be within ±10 percent of the true value two times out of three. This choice of criteria was arbitrary and probably sets a higher requirement for accuracy than is usually obtained or needed in this type of data.

Field observations supported the findings obtained by use of the electric analogue as to the small effect of obstructions. Even when stones were found to be near the base of the tube, a comparison with the mean values for the series of tubes indicated that the flow had not been seriously obstructed.

TABLE 1
TYPICAL FIELD TEST DATA

July 28, 1947 Water table above surface 6-in. head	Swenson Farm Story County, Iowa, Peat

	Fall of Water Level in Inches		
Tube No.	6-in Depth	12-in. Depth	18-in. Depth
1	5.49	3.94	2.20
2	3.81	3.58	2.82
3	5.01	2.81	2.48
4	3.47	3.06	2.06
5	4.02	3.28	2.60
6	1.44	3.61	3.10
7	0.52	3.24	2.63
8	0.95	3.71	2.72
9	2.31	3 55	2.73
10	1.56	3.57	2.61
11	5.63	2.95	2.17
12	5.20		
Summary of Data			
Av. Fall	3.28	3.39	2.56
St. Dev.	1.55	0.35	0.31
n*	32.3	1.1	1.5
Temp., deg C	20.6	18.9	17.2
Time in Min.	30.0	10.0	5.0
Permeability (in /hr.)	3.77	12.8	17.4

* n is the number of tubes needed to bring the average within ±10% of the true value ⅔ of the time.

The performance of the equipment was quite satisfactory. The driver was effective in quickly placing the tubes in a vertical position. While in some cases the soil slid from the rods of the soil remover, in general that device performed satisfactorily also. It was especially effective in breaking the soil in tension so as to give an undisturbed surface at the bottom of the tube. And the puller provided a quick and relatively easy method of removing the tubes.

DISCUSSION

Preliminary observations showed that the rate of flow into the tube was about five times greater than that from the tube for the same head differential. The difference was attributed to sealing of the soil pores by silt in the latter case. In order to obtain the true permeability, flow of water into the tube is recommended. The use of flow into the tube has the additional advantages of giving the permeability of the soil to soil water at soil water temperature.

It is felt that this procedure for soil permeability measurement has the advantages over commonly used methods in that it,

1. minimizes the disturbance in the natural structure of the soil
2. uses the soil water at the soil temperature and allows correction of readings to a standard temperature
3. eliminates the effect of trapped air when the soil has been saturated long enough for the air to have been absorbed in the soil water
4. minimizes the effects of irregularities in the soil by utilizing a fairly large area of the cross-section of sample.

As to the time needed to make field determinations under conditions encountered in this study, two men required 8 hours to make determinations at five depths with twelve tubes.

The method proposed here has serious limitations when used at very shallow depths. The data taken at 6 in. or less below the soil surface were not satisfactory because of the large variation in readings on different tubes. This variation may be ascribed to disturbance of the upper soil layer caused by tillage operations. Also, the method proposed for removing the soil from the tubes was not satisfactory for depths greater than 30 in. Finally, the procedure is suitable only for permeability measurements below the water table.

OTHER METHODS

Since developing the method described in this report, two other methods for measuring the permeability of soil in place have been developed at the Iowa State College Agricultural Experiment Station. The first of these methods utilizes the rate of rise of water in an auger hole bored into the soil below the water table, and the second the rate of rise of water into a pipe driven into the soil, soil having been removed from the pipe and to a small depth below the pipe before the rate of rise is observed. In both of these methods the electric analogue, essentially as developed and described above, is used to obtain the conversion factor to reduce the observed values to standard permeability units. In the special case of an auger hole which penetrates into or just reaches an impervious layer, however, the exact mathematical details of the problem have been solved and the electric analogue is not needed. The auger hole method will be described in the 1948 Proceedings of the Soil Science Society of America in two articles entitled "Theory of Seepage into Auger Holes" by Don Kirkham and C. H. van Bavel and "Field Measurement of Soil Permeability Using Auger Holes" by C. H. M. van Bavel and Don Kirkham. The pipe method will probably be published sometime in 1949, in an article by J. N. Luthin and Don Kirkham.

The auger hole method is, from a practical viewpoint, probably the simplest way conceivable for determining soil permeability. Hooghoudt (7) describes this method, but uses an erroneous analysis for converting the observed values to soil permeability. In the method, the water table level is first determined by letting water come to equilibrium in the bored hole. The hole is then pumped out and the rate of rise observed. The rate of rise, the distance of the hole below the water table and the radius of the hole are the only values that need to be known to determine the permeability.

In the pipe method, thin-walled electrical conduit tubing of 1-in. inside diameter is used. The pipe is driven a few inches into the soil, and then a soil auger of $\frac{15}{16}$-in. diameter is bored into the soil into the tube to a depth of about 4 in. below the bottom of the tube and the soil removed. The tube is then driven into the soil 4 in. and the augering process repeated. This process is continued until the bottom of the tube has reached the desired depth, there being finally a space 4 in. deep below the bottom of the tube.

The pipe method is essentially the same as the method described in the major portion of this report. It has the advantage over the method in which the 8-in. cylinders are used, in that there is no practical limit to which the pipe can be driven, the soil permeability thus being obtainable at any depth. In the pipe method the results may not be quite as accurate as those using the 8-in. cylinders. However, results obtained so far in uniform soil appear to be good. A Veihmeyer soil-tube jack with a special grip is used to remove the electrical conduits in the pipe method.

The auger hole method has an advantage over either of the other methods in that the "sample" is large. This can also be a disadvantage, for if the soil is stratified the permeability cannot be isolated at the several depths. The size of auger hole, used so far to best advantage, has been 4 in. in diameter.

It may be of interest to present the formula for use in the auger hole method when the auger hole just reaches an impermeable layer. This formula can be used to good approximation even in the absence of an impermeable layer if the ratio of depth to radius of the auger hole is large. The result is

$$K = (dh/dt)a^2/16\,dS,$$

where,

$$S = \frac{K_1(\pi a/2d)}{K_0(\pi a/2d)} \cos\frac{\pi h}{2d} - \frac{1}{3^2}\frac{K_1(3\pi a/2d)}{K_0(3\pi a/2d)} \cos\frac{3\pi h}{2d} + \frac{1}{5^2}\frac{K_1(5\pi a/2d)}{K_0(5\pi a/2d)} \cos\frac{5\pi h}{2d} - \cdots,$$

and

dh/dt = rate of rise of water in hole computed for the level h

h = distance of water level above bottom of hole at time t

d = distance of bottom of hole below water table

K = permeability of soil (inches per hours, if all other geometrical dimensions are in inches and time is measured in hours)

a = radius of hole

K_0 = Bessel function of second kind and zero order

K_1 = Bessel function of second kind and first order.

The Bessel functions noted above are tabulated in the British Association Mathematical Tables, Volume VI.

A final point in connection with the pipe and auger hole methods is that the soil opening must be pumped out one or more times, depending on the ease of puddling of the soil. This assures that the soil pores will be flushed out to their natural condition by the inflowing water and that therefore the rate of rise of water will be that due to the natural undistributed soil.

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