SPECIAL PUBLICATION

SP - SW-0262

measuring saturated hydraulic conductivity of soils

Published by the

ERICAN SOCIETY

OF

RAL ENGINEERS

St. Joseph, Michigan

price $.75

SPECIAL PUBLICATION
SP-SW-0262

measuring saturated hydraulic conductivity of soils

Published by the
AMERICAN SOCIETY
OF
AGRICULTURAL ENGINEERS
St. Joseph, Michigan

price $.75

MEASURING SATURATED HYDRAULIC CONDUCTIVITY

OF SOILS

Prepared December, 1959, by

Drainage Research Committee
Soil and Water Division
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Revised December, 1961

Approved for Publication by

Steering Committee, Soil and Water Division
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS
Saint Joseph, Michigan
June, 1962

MEMBERS* OF

ASAE DRAINAGE RESEARCH COMMITTEE

INVOLVED IN PREPARATION OF THIS PUBLICATION

Herman Bouwer, Agricultural Engineer, Southwest Water Conservation Lab., R. R. 2, Box 816-A, Tempe, Arizona

W. W. Donnan, Chief, Southwestern Branch, (SWCRD, ARS), USDA (Mail) P. O. Box 2326, Riverside, California

N. A. Evans, Head, Agricultural Engineering Department, and Irrigation Engineer, Colorado State University (Mail) 601 Miller Drive, Fort Collins, Colorado

F. R. Hore, Associate Professor, Department of Engineering Science, Ontario Agricultural College, Guelph, Ontario, Canada

R. C. Reeve, Irrigation and Drainage Engineer, U. S. Salinity Laboratory, ARS, USDA (Mail) P. O. Box 672, Riverside, California

G. O. Schwab, (Chairman when project initiated), Professor of Agricultural Engineering, Agricultural Engineering Department, Ohio State University Ives Hall, 2073 Neil Avenue, Columbus 10, Ohio

Phelps Walker, Agricultural Engineer, (SWCRD, ARS), USDA (Mail) Seitz Hall, V.P.I., Blacksburg, Virginia

R. J. Winger, Jr., Drainage Engineer, U. S. Bureau of Reclamation DFC (Mail) 4050 Ammons Street, Wheat Ridge, Colorado

Jan van Schilfgaarde, (Chairman when project completed), Research Associate Professor, Agricultural Engineering Department, North Carolina State College, Raleigh, North Carolina

* Affiliations listed for members are those on record at ASAE Headquarters, October, 1962.

CONTENTS

INTRODUCTION

No doubt the most important single property of soils affecting drainage design is the hydraulic conductivity. During the last 15 years, a large amount of research has been carried out on the development and evaluation of methods of measuring this soil characteristic.

To aid the uniniated research worker as well as the practicing engineer in making a choice of method suited to his particular need, it was felt desirable to make available an informal compilation of methods with an indication of their merits and limitations. Four years ago, the Drainage Research Committee of the ASAE set out to prepare such a compilation.

Unfortunately, the choice between methods is seldom black or white, and at the present state of technology there still is much disagreement between experts on the relative merits of many of the methods. Hence this compilation is not to be interpreted as a definitive evaluation, or even a tentative standard. Rather, it should be used as an introduction to the methods available and in common use, with some hints as to their pitfalls and limitations. The serious worker can then turn to the literature references for details on that method which most likely will suit his needs.

The project was initiated with G. O. Schwab as chairman. Correspondence and personal contact with numerous persons, both members and nonmembers of ASAE, have contributed to the material here presented.

PIEZOMETER METHOD

1. The method

A seamless tube is installed by augering out a hole 6 inches at a time and then driving the tube to 1 inch from the bottom of the hole. The auger should be 1/16-inch less in diameter than the inside diameter of the tube. Upon reaching the desired depth, a cylindrical cavity of known length is augered out below the tube.

Water rising into the hole is removed several times by pumping or bailing in order to flush the soil pores along the cavity wall. After flushing, the water is left to rise to equilibrium with the water table. It is then pumped out again and the rate of rise is noted by means of an appropriate water level indicator and stop watches.

To convert field data to hydraulic conductivity, one uses the relation

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

where K is the hydraulic conductivity, R the radius of the cavity, h_1 and h_2 the heights of the water level below the equilibrium level at times t_1 and t_2, and A a factor depending on the geometry of the flow system (dimensions of length). Values for the A-function are given by Luthin and Kirkham (1949). See also Luthin (1957).

2. Equipment and dimensions

a. Tube size reported varies from 1/2" pipe to 2" thin-walled electrical conduit. Predominant sizes: 1, 1-1/2, 2" thin-walled.

b. Cavity length: predominantly 4".

c. To remove water: pitcher pump with flexible tube or cylindrical bailer with valve at bottom.

d. To record water level: float with calibrated stick attached, or electric indicator.

3. Merits and limitations

The method is well suited to determining the conductivity of layers in stratified soil if the layers are homogeneous and isotropic within themselves and not "too" thin. In anisotropic soils, the method measures predominantly the horizontal conductivity.

Measurements near an impermeable layer result in considerable errors unless appropriate corrections are made in the A-function. The distance from cavity to tight layer must be at least 1/2 the cavity length.

The method is not reliable when root holes and worm holes are present or in highly structured soils, and is unsuited in stony soils because of damage to the piezometers. The diameter of the cavity affects the calculations greatly so that stable cavity walls are mandatory for repeatable results. Nelson (1957) used a type of well screen to line the cavity with success.

4. References

Ayers, H. D., 1951. Soil permeability as a factor in the translocation of salts on irrigated land. Sci. Agri. 31:383-395

Frevert, R. K. and Don Kirkham. 1948. A field method for measuring the permeability of soil below the water table. Proc. Hy. Res. Bd. 28:433-442.

Hore, F. R., 1959. The Piezometer Method--A symposium on field experiences in measuring hydraulic conductivity for drainage design. Edited by W. W. Donnan. Agric. Eng. 40:270-273, 280.

Johnson, H. P., R. K. Frevert and D. D. Evans. 1952. Simplified procedure for the measurement and computation of soil permeability below the water table. Agr. Eng. 33:283-286.

Kirkham, Don. 1955. Measurement of the hydraulic conductivity' of soil in place. Symposium on permeability of soil. ASTM Spec. Tech. Pub. 163:80-97.

Luthin, J. N. and Don Kirkham. 1949. A Piezometer method for measuring permeability of soil in situ below a water table. Soil Sci. 68:349-358.

Luthin, J. N., Editor, 1957. Drainage of Agricultural Lands. Am. Soc. Agron., Madison, Wisconsin.

Nelson, R. W. 1957. Measurement of hydraulic conductivity in unstable soils with the piezometer method. Paper prepared for drainage specialists of engineering watershed planning units of Soil Conservation Service.

Reeve, R. C. and M. C. Jensen. 1949. Piezometers for ground water flow studies and measurement of subsoil permeability. Agr. Eng. 30:435-438.

__________ and Don Kirkham. 1951. Soil anisotropy and some field methods for measuring permeability. Trans. A.G.U. 32:582-590.

Talsma, T. 1960. Measurement of soil anisotropy with piezometers. (British) J. Soil Sci. In press.

__________ 1960. Comparison of field methods of measuring hydraulic conductivity. Trans. Congress on Irrigation and Drainage IV (6):C145-C156.

__________ and H. C. Haskew. 1959. Investigation of water table response to tile drains in comparison with theory. Trans. A.G.U. 64:1933-1944.

Van Bavel, C. H. M. 1952. Discussion of Reeve and Kirkham (1951). Trans. A.G.U. 33:461.

AUGER HOLE METHOD

1. The method

A hole is augered out to the desired depth below the water table and water is allowed to rise until in equilibrium with the water table. The hole is then emptied by bailing or pumping and the rate of rise of water level in the hole is measured at different depths below the water table.

The calculation of hydraulic conductivity is performed with the equation

$$K = \frac{\pi R^2}{Ah} \frac{dh}{dt}$$

where R again refers to the radius of the auger hole, h to the hydraulic head, t to the time and A to the geometry factor. This equation may be written in the form

$$K = \frac{2\pi R^2(h_1 - h_2)}{A(t_2 - t_1)(h_1 + h_2)} .$$

Since A varies with h, it is important that $(h_1 - h_2)$ be kept small. Values of A for different values of R/d and S/d are available (Johnson et al); these are only applicable when h/d is less than 0.2. Here d is the depth of the hole below the water table and S the distance of the bottom of the hole from an impermeable layer. See also Luthin (1957). The equation may also be written as

$$K = C\, dh/dt$$

where C corresponds to the factor $2\pi R^2/A(h_1 + h_2)$ in the previous equation. Graphs of C are available for $S = 0$ and $S = \infty$. (Ernst, or Maasland and Haskew).

2. Equipment and dimensions

Auger holes from 1/2 inch to 4 inches in diameter have been used. Depths greater than 4 or 5 feet are often impractical; however, there is no theoretical limitation as to depth. It is very important to maintain the cavity shape; screens have been used by some (Van Beers) to serve this purpose. Emptying the hole and measuring water level rise may be done with the same equipment as in the piezometer method. A base plate or tripod is needed as reference level and for electrical ground to replace the piezometer top which serves these functions in the piezometer method.

3. Merits and limitation

The auger hole method is simplest of all methods in conception and in field practice. It measures a far larger sample than most other methods, and requires less time, equipment and labor per measurement than does the piezometer method. It measures some kind of "mean" conductivity over the depth of the hole below the water table, and predominantly the horizontal component of K in anisotropic soil. Thus it cannot be used effectively in layered soils unless the layers have nearly equal values of K. Also in soils where underground channeling is prevalent from, say, roots or animals, the method is unreliable. Partial collapsing of the hole makes the determinations very unreliable.

4. References

Diserens, E., 1934. Beitrag zur Bestimmung der Durchlässigkeit des Bodens in Natürlicher Bodenlagerung. Schweizerische Landw. Monathefte. 12:188-198, 204-212.

Ernst, L. F., 1950. A new formula for the calculation of the permeability factor with the auger hole method. T.N.O. Groningen.

Hooghoudt, S. B., 1936. Bijdragen tot de Kennis van Eenige Natuurkundige Grootheden van den Grond, 4. Versl. Land. Ond. 42(13) B:449-541.

Johnson, H. P., R. K. Frevert and D. D. Evans. 1952. Simplified procedure for the measurement and computation of soil permeability below the water table. Agr. Eng. 33:283-286.

Kirkham, Don., 1946. Proposed method for field measurement of permeability of the soil below a water table. Proc. Hway. Res. Bd. 28:433-442.

________. 1955. Measurement of the hydraulic conductivity of soil in place. Symposium on permeability of soils. ASTM Spec. Tech. Pub. 163:80-97.

Luthin, J. N., Editor. 1957. Drainage of Agricultural Lands. Am. Soc. Agron., Madison, Wisconsin.

Maasland, Marinus and Henry C. Haskew. 1957. The auger hole method of measuring the hydraulic conductivity of soil and its application to the drainage design. Proc. 3rd. Int. Conf. Irr. Drain. 8.69-8.114.

Reeve, R. C., and Don Kirkham. 1951. Soil anisotropy and some field methods of measuring permeability. Trans. AGU. 32:582-590.

Van Bavel, C. H. M. and Don Kirkham. 1949. Field measurement of soil permeability using auger holes. Proc. SSSA. 13:90-96.

Van Beers, W. F. J., 1958. The auger hole method. Bul. Nr. 1. Intern. Inst. Land Recl. and Improvement. Wageningen, The Netherlands.

POMONA WELL POINT METHOD

1. The method

A King soil tube is driven approximately to the depth desired. The well point is then inserted into the empty soil tube and both devices are lowered into the hole. The well point is then pushed on down six or eight inches beyond the soil tube into the stratum where the measurement is to be made. For King tube, see Wiley, pp.79-80.

The water table is allowed to come to equilibrium and its position is measured. Then a small diameter suction tube is lowered inside the well point to a point three inches below the water table. By pumping, a 3-inch head difference is maintained and the rate of outflow is measured. The conductivity is determined from

$$K = Q/Gh$$

where Q is the discharge rate, h the head difference and G a geometry factor corresponding to the A-factor in the piezometer method.

2. Equipment and dimension

The well point is made of a 1/4-inch galvanized nipple 4 inches long threaded into a 3-foot length of 3/8-inch galvanized pipe on one end. On the other end is screwed a cap made of a 1/4-inch coupling and plug. The nipple is perforated with 20 1/8-inch holes and covered with a 3"-long, cylindrical, 40-mesh, brass screen, made of a 2x3-inch square, which fits snugly between the coupling and the 3/8-inch pipe. The cap is ground to a cone.

Pumping can be done with a Ford fuel pump or by connecting to the vacuum of a car motor.

3. Merits and limitations

The device is simple and cheap. Because of the fixed dimensions of the flow system, the geometry factor stays the same at all times (7.5 inches for the dimensions given). Layered soils can easily be investigated and the soil need not support a cavity. The method works well in sands, but not very well in clays or clay loams.

4. Reference

Donnan, W. W., and V. S. Aronovici, 1961. Field measurement of hydraulic conductivity. Proc. Am. Soc. Civil Eng., 87:IR2:1-13.

Wiley, Harvey W., 1906. Principles and Practice of Agricultural Analysis. 2nd. Edition, Volume 1. Chemical Publishing Company.

SHALLOW WELL PUMP-IN METHOD

1. The method

The shallow well pump-in method, also referred to as the well-permeameter method or the dry auger hole method, consists basically of measuring the rate of flow of water from a cased or uncased auger hole when a constant height of water is maintained in the hole.

The hole should be carefully prepared and the sides should be brushed or scraped to remove any compaction or sealing on the periphery and loose soil should be removed from the bottom. A thin-walled casing is installed with perforations from the bottom to the predetermined water level. The hole may be filled with uniformly sized sand to about six inches below the intended water level.

A float valve such as a carburetor is used to maintain the water level and a large sized tank is used to provide the required water.

The daily rate of water use is determined until a (nearly) steady state is obtained. At that time, the conductivity may be calculated from nomographs (such nomographs have been prepared by the U. S. Bureau of Reclamation) or from formulas. The water temperature can be measured to correct daily flow rates for viscosity. The position of the water table or impermeable layer below the test hole must be ascertained to enable selection of the proper nomograph.

A method very similar in principle but quite different and more elaborate in apparatus, has been developed by Sillanpää. However, his method seems to offer no significant advantages over the one described above.

2. Equipment and dimensions

a. A 4-inch auger is recommended.

b. 4-inch round downspout can be used for casings; perforations should cover at least 20% of area.

c. Sand for filter should pass #14 screen and be retained on a #24 screen.

d. Tank should be about 50 gallons; a larger tank may be needed to haul water to the field.

3. Merits and limitations

The obvious important advantage of the method is that the conductivity can be determined above, or without the presence of, the water table. Disadvantages are the expense and the time required for completing measurements. Furthermore, notwithstanding reasonable precautions, the values of K obtained this way are lower than actual (as determined with, say, the auger hole method). The difference may be a repeatable factor depending on the magnitude of K, as suggested by Talsma. The ratio of pump-in-method K to auger-method K is estimated to be on the order of 0.50 by Talsma, and 0.85 by Winger. Sillanpää (1959) shows a range from 0.72 to 1.97.

4. References

Office of Drainage and Groundwater Engineering, Bureau of Reclamation, Denver, Colorado. Field determination of hydraulic conductivity by shallow well pump-in tests. March 19, 1958.

Jones, C. W., 1951. Comparison of seepage based on well-permeameter and ponding tests. Earth Materials Laboratory Report EM-264, Bureau of Reclamation, Denver, Colorado.

Sillanpää, Mikko, 1956. Studies on the hydraulic conductivity of soils and its measurement. Acta Agr. Fenn. 87, 109 p.

________. 1959. Comparison of some field methods of measuring hydraulic conductivity of soils. Acta Agricultura Scandinavica IX:59-68.

Talsma, T., 1960. Comparison of field methods of measuring hydraulic conductivity. Trans. Congress on Irrigation and Drainage IV (6):C145-C156.

CYLINDER PERMEAMETER METHOD

1. The method

The cylinder permeameter method is similar to the shallow well, pump-in method in that in both cases water is added to a dry auger hole above the water table. However, the ring permeameter method uses a far larger diameter hole at the center of which is placed an 18-inch diameter cylindrical sleeve. This sleeve is made to penetrate the soil some 6 inches below the bottom of the hole. When the same water level is maintained both inside and outside the cylinder in the hole, and the rate of water intake is measured from inside the cylinder, vertical conductivity can be calculated if the pressure near the bottom edge of the cylinder is known. To this purpose, two tensiometers and two piezometers are placed at the same elevation as the bottom edge of the cylinder and inside it. Darcy's law, $K = QL/HA$, is used. Here Q is the rate of flow, H/L the hydraulic gradient across the soil sample inside the cylinder, and A the cylinder cross-sectional area. The tensiometers are used to determine the tension at the bottom of the ring. When they indicate about zero tension, saturation is assumed. As long as the piezometers remain empty, there is no build-up of pressure resulting from a restricting layer or a natural water table. It is recommended that no measurements be made after positive pressures have developed in the 6-inch test zone.

2. Equipment and dimensions

a. Hole diameter: 42 inches.

b. Cylinder size: 18-inch diameter x 20 inches long.

c. Water supply: 25-50 gallon tank calibrated to nearest cubic inch (say with side glass).

d. Two mercury manometers.

e. Two 1/2-inch piezometers.

f. Driving equipment for cylinder and piezometers.

g. Water level control: carburetor.

3. Merits and limitations

a. Enables determination of K above or without a water table, and of individual layers of soil.

b. Measures vertical component of conductivity.

c. Somewhat simpler in theory than well-permeameter method.

d. As described here, suffers from head loss across water-soil interface, and thus results in lower than actual K-values.

e. This method is here described according to Winger and as used within the U. S. Bureau of Reclamation. The following comments are made without benefit of field trial. It appears that the tensiometers could be used for both tension and pressure measurements, obviating the need for the piezometers. The assumption of saturation at zero pressure is not correct and probably results in an underestimate of the saturated conductivity. The undesirable head loss at the surface could be circumvented by using tensiometers at two elevations, using the hydraulic gradient between these two levels for the calculations. No serious objection is seen against use of data obtained after positive pressures have been obtained, since the flow will still be essentially one-dimensional; however Winger's experience suggests more reliable results if positive pressures are avoided.

4. References

Winger, R. J., 1956. Field determination of hydraulic conductivity above a water table. Presented at Winter Meeting, ASAE, Chicago, Illinois.

DOUBLE TUBE METHOD

1. The method

As with the ring-permeameter method, the double tube method permits determination of K above a water table by observations of water from two concentric cylinders. An auger hole is dug to the depth at which a measurement of K is desired. An undisturbed soil surface is approximated at the hole bottom with a specially designed hole cleaner; this surface in turn is protected with a thin layer of sand. Two concentric cylinders with diameter ratio 1.7 or larger are carefully installed with penetration of 3/4 to 1 inch into the soil. Water is added to both cylinders, care being exercised that the water level in both tubes stays very nearly the same during filling. Standpipes of equal heights are attached to both cylinders. After initial filling both standpipes are kept full. With time, a wet zone with positive pressures builds up, considered to be (but not truly) at saturation. After several hours, the water supply to the inside tube is cut off. The water level in this tube will start to fall and, by manipulating a valve, the level in the outer tube is kept equal to that in the inner tube. Measurements of height of drop versus time permit the plotting of an "equal level" H-t curve. Next, the water levels are brought back to the same starting point and, after a reasonable delay (10 times the time required to obtain the actual measurement), the rate of drop of the level in the inside tube is measured with a constant level in the outer cylinder, and a "constant level" H-t curve is plotted.

The conductivity is determined from the relation

$$K = \frac{R_v^{\,2}}{FR_c} \; \frac{\Delta H_t}{\int_0^t H\,dt},$$

where R_v is the radius of the inside cylinder standpipe, R_c the radius of the inside cylinder, ΔH_t the difference in ordinates between the "constant level" and "equal level" curves at time t and the integral represents the area under the "constant level" curve up to the same time t. H is the height of the water level below the top of the standpipes. F is a flow factor, analogous to the A-factor of other methods, and available from graphs obtained with electric resistance network experiments.

2. Equipment and dimensions

a. Auger hole and cylindrical sleeve--8 inches.

b. Inside cylinder (centered with guide vanes)--5 inches.

c. Water supply--about 100 gallons per test.

d. Top seal and standpipe arrangement.

e. Hole cleaner.

3. Merits and limitations

a. Enables conductivity measurement in absence of water table.

b. Is based on flow component from outside to inside cylinder, thus eliminating dependence on intake rates and partially on surface sealing.

c. Method free of stringent simplifying assumptions.

d. Sample area is fairly well defined; depth of zone affecting measurements is about twice inside cylinder radius.

e. Air entrapment and non-uniformity or anisotropy in sampled area are major sources of error.

4. References

Bouwer, Herman, 1961. A double-tube method for measuring hydraulic conductivity of soil in situ above a water table. Soil Sci. Soc. of Am. Proc. 25:334-339.

_____________, 1962. Field determination of hydraulic conductivity above a water table with the double tube method. Soil Sci. Soc. of Am. Proc. 26:330-335.

_____________,1961. Application of the double tube method for field measurements of hydraulic conductivity of soil above the water table. Presented, ASAE Winter Meeting, Chicago. Paper number 61-709.

CORE SAMPLE METHOD

1. <u>The method</u>

Cylindrical samples of soil are obtained by standard techniques, using a Lutz sampler, an Uhland sampler or a similar device. The samples are kept from drying out by placing them in waxed cartons or close-fitting metal sample cans or other suitable wrapping or container.

After saturating the samples from the bottom, they are placed on a platform and arranged so that water is supplied to the bottom of the samples at a constant hydraulic head. Measuring the outflow periodically gives the data necessary for calculation of K with the equation*

$$K = \frac{QL}{Ah} \times \frac{\mu}{\mu_s} .$$

Here h refers to the hydraulic head differential and Q to the discharge rate; A and L refer to the sample area and length; μ and μ_s are the viscosity of water at the temperature of the test and at 20°C, respectively.

2. <u>Equipment and dimensions</u>

   a. Sample size of 3 x 3 inches seems most prevalent. At Minnesota, samples of 5-inch diameter x 6-inch length are used.

   b. Effective head should be small, say 1 or 2 inches.

3. <u>Merits and limitations</u>

   a. Does not require a water table.

   b. Enables sampling of layers and in desired directions of layered or anisotropic soils.

   c. Relatively cheap.

   d. Small sample volume.

*This temperature correction should be applied to <u>all</u> methods!

e. Compaction during sampling.

f. Loss of head at interface between water and soil.

g. Because of above: greater variability of results than in, say, auger hole method and generally a lower value. Talsma reports a ratio between measurements of (Core)/(Auger hole) of about 0.15.

h. The 5" samples seem less variable than the 3" samples and to suffer less from compaction, according to C. L. Larson (University of Minnesota).

4. References

Devereux, R. E., Steele, F., and Turner, W. L. Jr. 1951. Permeability and land classification for soil and water conservation. Proc. SSA 15:420-423.

Hoover, Marvin D. 1949. Hydrologic characteristics of South Carolina Piedmont forest soils. Proc.SSSA. 14:353-358.

Lutz, J. F., et al. 1947. Effects of cover crops on pore-size distribution in a coastal plain soil. Proc. SSSA. 11:43-46.

Mason, D. D., J. F. Lutz and R. G. Petersen. 1957. Hydraulic conductivity as related to certain soil properties in a number of Great Soil Groups--Sampling errors involved. Proc. SSSA. 21:554-560.

O'Neal, A. M. 1952. A key for evaluating soil permeability by means of certain field clues. Proc. SSSA 16:312-315.

Peele, T. C. 1950. Relation of percolation rates through saturated soil cores to volume of pores drained in 15 and 30 minutes under 60 centimeters tension. Proc. SSSA. 14:359-361.

Reeve, R. C. and J. N. Luthin. 1957. Methods of measuring soil permeability. Drainage of Agricultural Lands, Agronomy Monograph 7:395-445.

Uhland, R. E. and O'Neal, A. M. January 1951. Soil permeability determinations for use in soil and water conservation. USDA SCS-TP-101.

Walker, Phelps. 1952. Depth and spacing for drain laterals as computed from core-sample permeability measurements. Agr. Engr. 33:71-73.

SYNOPSIS

If the information that was gathered by this committee could be summarized and generalized into a few valid observations, these would read something like the following:

1. Methods using water flowing <u>into</u> a hole from the surrounding soil are preferable to those where water flows <u>out</u> of the hole. The reason lies in the <u>lower</u> value for K found in the latter case, resulting probably from clogging of the pores.

2. In comparing methods below a water table, the variability of measurements varies roughly inversely with sample size; thus we have in order of preference auger hole, piezometer, Pomona, tube (not discussed explicitly), core methods. (Note: core method not properly compared here.)

3. Special conditions will result in other orders of suitability: Pomona well point for unstable soils; piezometer for stable, layered soils; auger hole for stony soils.

4. When conditions without a water table prevail, the methods with water flowing <u>out</u> of the hole must be used. No evidence was submitted to show preference of one method over another. The cylinder permeameter method probably is cheaper than the well-permeameter method. The double tube method deals with a somewhat better defined flow system. Sample size and effect of anisotropy and heterogeneity affect the three methods quite differently. Air entrapment can be a serious handicap in all three methods.

5. The core method generally gives greatly reduced values for K, but it is not clear whether a relation can be established so that "true K" can be estimated from "core K". Also, variability of core measurements is greater than in most other methods.

6. <u>An estimate as to time required for field work</u>:

   Auger hole method*- 1/2 man-hour/measurement.
   Tube method*- 3/4 man-hour/measurement.
   Piezometer method*- 1 man-hour/measurement.

*In teams of two--modified after Hore, Kirkham, Talsma and personal experience. These values assume that several observations will be made from the same setup and that a large number (more than 10) of holes are chosen in one rather small area. Times would be longer for single measurement from each setup and for widely scattered locations.

Ring permeameter method - 2 to7 days.
Well permeameter method - 2 to7 days.
Double tube method - 5 to10 hours.

7. Reproducibility

Estimates of coefficient of variation modified from Talsma, Kirkham and others:

Piezometer	cv = 25
Auger hole	cv = 10
Core	cv = 200+ ?