THE PREDICTION OF UNSATURATED FLOW RATES FROM PHYSICAL PROPERTIES OF THE POROUS MEDIUM

Project Completion Report

prepared by

Larry L. Boersma

The work upon which this report is based was supported in part by funds provided by the Office of Water Resources Research, Department of the Interior, through the Water Resources Research Institute of Oregon State University as authorized under the Water Resources Research Act of 1964 and matching grant funds from the Oregon State University Agricultural Experiment Station.

Project No. B-001-ORE

Matching Grant Agreement

No. 14-01-0001-884

December 31, 1970

PERTINENT INFORMATION

Project No.: B-001-ORE

Matching Grant Agreement No.: 14-01-0001-884

Project Leader: L. Boersma
Department of Soils
Oregon State University
Corvallis, Oregon 97331

Institution: Oregon State University
Corvallis, Oregon 97331

Period during which research was conducted:

Funded period: January 1, 1966 - February 28, 1969
Non-Funded period: March 1, 1969 - June 30, 1971

Date of Completion Report: December 31, 1970

Graduate students supported by the project:

G. O. Klock, Ph.D. degree

present address: U.S. Forest Service
Forest Hydrology Laboratory
Wenatchee, Washington 98801

thesis (June 1968): Pore Size Distributions as Measured by the Mercury Intrusion Method and Their Use in Predicting Permeability.

Ahang Kowsar, M.S. degree

present address: Research Institute of Natural Resources
Elizabeth Blvd.
Tehran, Iran

thesis (June 1968): Effect of Petroleum Mulch on Soil Water Content and Soil Temperature.

Narender Kumar Nagpal, Ph.D. degree

present address: Department of Soils
Oregon State University
Corvallis, Oregon 97331

thesis (to be presented December 1970): Physical Properties of Soils.

Subodh Kumar Saxena, Ph.D. degree

present address: Department of Soils
Oregon State University
Corvallis, Oregon 97331

thesis (to be presented June 1971): Prediction of Diffusion Rates in Soils.

Papers published:

G. O. Klock, L. Boersma and L. W. DeBacker. Pore Size Distribution as Measured by the Mercury Intrusion Method and Their Use in Predicting Permeability. Soil Sci. Soc. Amer. Proc. 33(1):12-15, 1969.

Ahang Kowsar, L. Boersma and G. D. Jarman. Effects of Petroleum Mulch on Soil Water Content and Soil Temperature. Soil Sci. Soc. Amer. Proc. 33(5):783-786, 1969.

Papers being processed for publication:

N. K. Nagpal and L. Boersma. Use of the Mercury Intrusion Method to Obtain Soil Water Characteristic Curves.

F. T. Lindstrom and L. Boersma. A Theory on the Mass Transport of Previously Distributed Chemicals in a Water Saturated Sorbing Porous Medium. Accepted for publication in Soil Science.

S. K. Saxena and L. Boersma. Prediction of Diffusion Coefficients in Porous Media.

OBJECTIVES

The only methods which make it possible to obtain water transmission coefficients of porous media without the use of complicated experimental techniques are prediction methods based on physical properties of the medium. Because agreement between calculation methods and experimentally obtained values has not been good, scientists and engineers have been reluctant to use these methods. The initial purpose of the research reported here was to develop simple laboratory techniques to measure the physical properties needed in these prediction methods and to check these methods through a series of systematic measurements. The objectives were stated as follows:

1. To establish a relationship between water transmission coefficients of a porous medium and the physical properties of the medium by a series of systematic measurements.
2. To develop a method by which water transmission coefficients for any porous material may be predicted reliably without the need of complicated experiments.
3. To establish the possible use of a mercury intrusion porosimeter as a tool for the routine measurement of pore size distribution.
4. To compare values of water transmission coefficients calculated from pore size distributions with experimentally obtained values.

After the time period allowed for the project terminated and funding ceased, two graduate students initially employed on this grant were still in the process of completing their theses. For their work the objectives were enlarged to include an investigation of the relation between thermal and diffusive transfer characteristics and pore size distributions as determined by the mercury intrusion method as well.

EXPERIMENTS CONDUCTED

Water Transmission Coefficients

Several methods have been proposed by which the permeability of a porous medium may be calculated from the pore size distribution of the medium. Presently, pore size distributions for soils are obtained from soil water release curves. This method has certain limitations. Replication of pore size distributions are difficult to obtain. The measurements are time consuming.

Development of a technique to measure pore size distributions, first used by Drake and Ritter (1945a and 1945b) in their work with chemical powders, may overcome some of the drawbacks of using liquid release curves. This technique is based on forcing mercury into the porous material. Pore size dsitributions are then obtained from the pressure of displacement equation and the volume of mercury forced into the porous material. The procedure is simple to use and does not take much time.

Pore size distributions were determined for several porous media with a wide range in particle sizes using a mercury intrusion porosimeter. The materials were obtained by separating glass beads and sands into different size fractions.

Pore size distributions were determined by the mercury intrusion method. The mercury intrusion porosimeter is an instrument by which pressure can be applied to a reservoir of mercury in contact with a porous solid sample. Precise measurement of changes in the volume of mercury as the pressure is increased provides a measure of the volume of pores in a given size range. To use the mercury intrusion porosimeter certain modifications had to be developed for commercially available equipment. The actual measuring device used is shown in Figure 1. Pore size distributions for two soils are shown in Figure 2.

The intrinsic permeability of each material was calculated by Millington and Quirk's (1959, 1961) equation.

$$K = \frac{\varepsilon^{4/3}}{8n^2} \Sigma\, r_1^{\,2} + 3r_2^{\,2} + \ldots\ldots (2n-1)r_n^{\,2})$$

where K is the permeability, ε is the porosity, r is the average pore diameter for a given pore size increment, and n is the number of pore size increments into which the total pore volume is divided.

The permeabilities of the materials were measured with a constant head permeameter. Bulk densities and porosities were obtained with gamma ray attenuation equipment.

A total of 63 samples was tested with permeabilities ranging from 1.5 - 39.1 μ^2 . The mathematical relationship between calculated permeability K_c and measured permeability K_m is given by the regression equation,

$$K_c = 0.583\ K_m + 0.39 \qquad r = 0.981$$

The disagreement between measured and calculated result ($K_c \neq K_m$) may be the result of either an error in the measurement of pore aperture or the inability of the equation used to predict permeability correctly. A theory was developed showing how the pore aperture measured by the mercury intrusion method underestimates the pore cross section available for flow. In accordance with this theory a modified form of Millington and Quirk's equation (1959) was proposed.

$$K = \frac{1.71\ \varepsilon^{4/3}}{8n^2}\ \Sigma\ (r_1^{\ 2} + 2r_2^{\ 2} + \ldots\ldots (2n-1)r_n^{\ 2}$$

Soil Water Characteristic Curves

The relation between soil water content and matric suction is usually referred to as the soil water characteristic curve. These curves are needed for example in estimating the amount of water available for plant growth in a given soil and to determine the amount of water to be applied at each irrigation cycle. This information is essential for efficient use of water in irrigation. The curves are obtained by a method introduced by Richards (1941, 1948, 1949). Since soil water characteristic curves are an expression of pore size distribution, mercury intrusion offers a unique opportunity to gain the information needed to construct these curves. The advantages of such a procedure would be that it is much faster than the standard pressure plate technique and that the range of capillary pressure is considerably greater than for the porous plate or membrane method.

A series of experiments was conducted to compare soil water characteristic curves obtained by means of mercury intrusion with those obtained by conventional techniques. Two examples are shown in Figures 3 and 4.

Examination of the two figures indicates that the soil water characteristic curves obtained by the two methods agree well for soils with low clay content (Figure 3) but do not agree for soils with appreciable amounts of clay (Figure 4). For soils with high clay content the two curves can be made to coincide by transposing the curves obtained by the mercury intrusion method. The degree of transposition is a function of the clay content. This is shown in Figure 5 where the degree of transposition required is plotted as a function of the clay content of the soil.

A procedure has been outlined for the determination of soil water characteristic curves by means of mercury intrusion. It allows correction for the observed discrepancy on the basis of the clay content of the soil. This procedure is much faster than currently used techniques and a great deal more reproducible.

Thermal Conductivity

The thermal conductivity of the soil is an important parameter in the study of many processes occurring in nature. In a porous medium not completely saturated with water the heat transfer occurs by conduction through solid particles and water films surrounding the solid particles as well as by movement of water in liquid and vapor form. It was considered important to evaluate the effect of pore size distribution of a soil on its thermal conductivity since all transfer mechanisms involved may be expected to be pore size dependent.

The thermal conductivity of three porous materials was measured as a function of water content. The materials consisted of glass beads in these sizes: (a) 149-210 μ , (b) 74-105 μ , and (c) 55-74 μ . Results of the measurements are shown in Figure 6. It indicates that as the water suction increases the thermal conductivity rapidly declines. The thermal conductivity of the coarsest soil decreases at the lowest suction. This graph reflects the loss of water in the suction range where the conductivity decreases and not an effect of pore size on either vapor transfer or water transfer. The most important parameter determining the thermal conductivity of a soil is its water content. It is only through its influence on this parameter that pore size distribution is important.

Transport of Chemicals in Porous Media

Several models have been proposed to predict the transport of chemicals in porous media. In these models the soil is usually considered as a uniform medium with an average pore size. The actual pore size distribution of the medium is then represented by this average pore size. It was postulated that the dispersive equations including the diffusion and convection terms can be improved by considering the actual pore size distributions of the medium. The theory developed is in part based on the assumption that

1. the voids in the pores medium are made up of n pore size increments, each with an average pore radius r_j
2. the longitudinal dispersion coefficient D_{oj} be represented by the equation

$$D_{oj} = D_0 \ (1-e^{-\lambda r_j^2})$$

where D_{oj} is a longitudinal dispersion coefficient (cm^2/day) in the j th pore, D_o is the free chemical diffusion (cm^2/day) in bulk solution, and r_j is the j th pore radius.

Experiments were initiated to measured D_o for certain herbicides. These chemicals were studied because of the importance of the translocation of such chemicals in soils. Further experiments are being conducted to evaluate the functional relationship postulated in the above equation. Figure 7 shows the influence of pore size on diffusion of chemicals.

DEGREE OF ACCOMPLISHMENT OF OBJECTIVES

Objectives 1, 2 and 4: The permeability of the inert porous materials considered can be predicted reliably when the pore size distribution is known.

Recommendation: Further experiments should be conducted to evaluate the procedure for shrinking and swelling soils.

Objective 3: Mercury intrusion is an efficient and highly reproducible method to obtain the pore size distribution of soils. This technique is now used in the Soils Department at Oregon State University in almost all instances where knowledge of the pore size distribution is important. The use of the instrument has been made a standard laboratory exercise in classes in laboratory techniques.

Recommendation: Additional experiments are required to improve the procedure for obtaining soil water characteristic curves from mercury intrusion data for certain problem soils.

Further objectives: Mercury intrusion data can be used very successfully to provide the quantitative information required in transport models for water, heat and chemicals in porous media. Such problems arise in

a. the study of leaching problems

b. the study of problems on the translocation of agricultural chemicals

c. the study of groundwater problems

d. the study of energy budget problems

REFERENCES

Drake, R. L. and L. C. Ritter. 1945a. Pore size distributions in porous materials. Industrial and Engineering Chemistry, Analytical ed., 17:782.

_______________ 1945b. Macropore size distributions in some typical porous substances. Industrial and Engineering Chemistry, Analytical ed., 17:787.

Millington, R. J. and J. P. Quirk. 1959. Permeability of porous media. Nature 183:387-388.

_______________ 1961. Permeability of porous solids. Faraday Society, Transactions 57:1200-1206.

Richards, L. A. 1941. A pressure-membrane extraction apparatus for soil solution. Soil Science 51:377-386.

_______________ 1948. Porous plate apparatus for measuring moisture retention and transmission by soil. Soil Science 66:105-110.

_______________ 1949. Methods of measuring soil moisture tension. Soil Science 68:95-112.

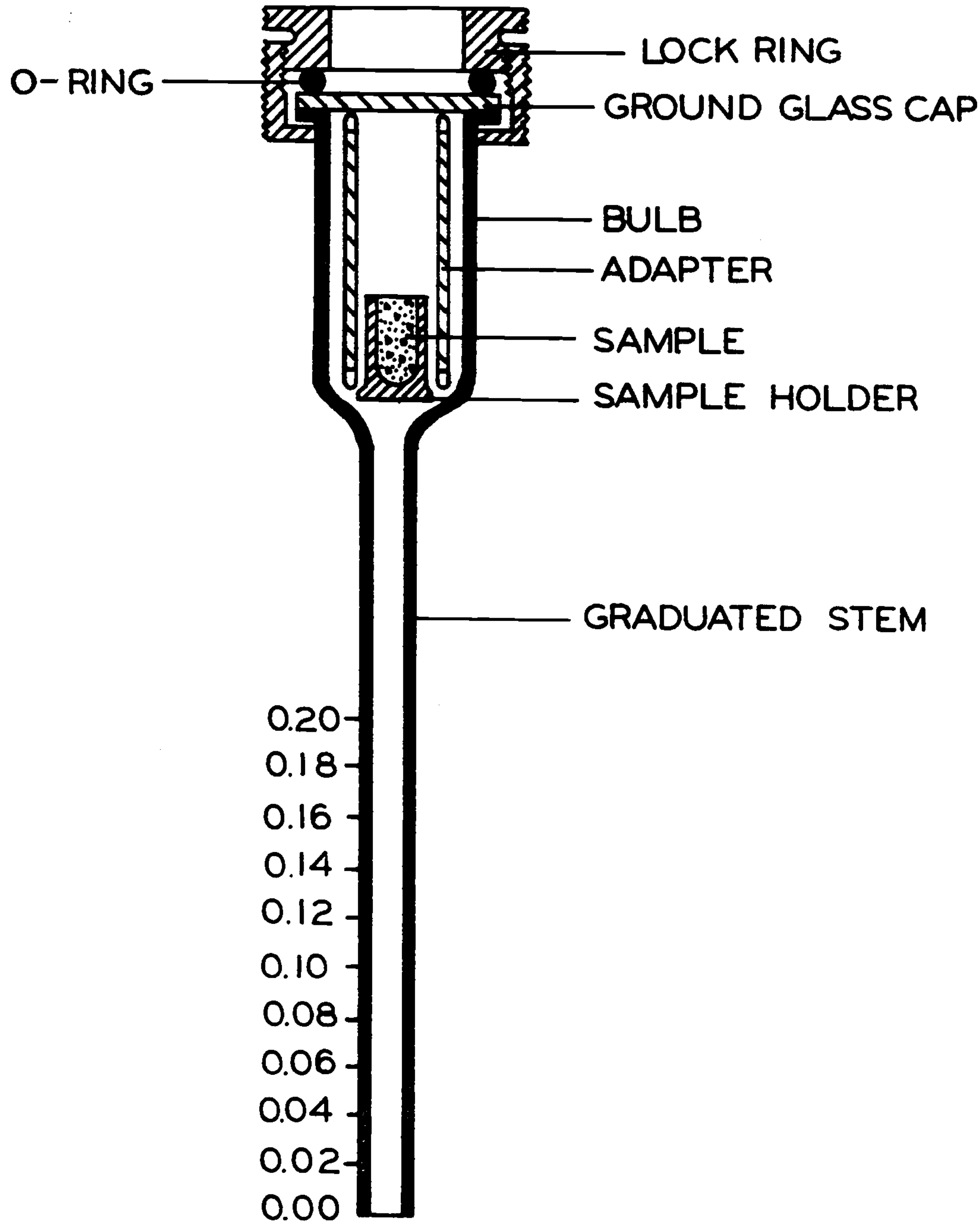

Figure 1. Penetrometer for the mercury intrusion porosimeter. The sample holder consisting of a glass cup with holder was developed for the experiments described. A contained sample was required for control of the packing of the material used.

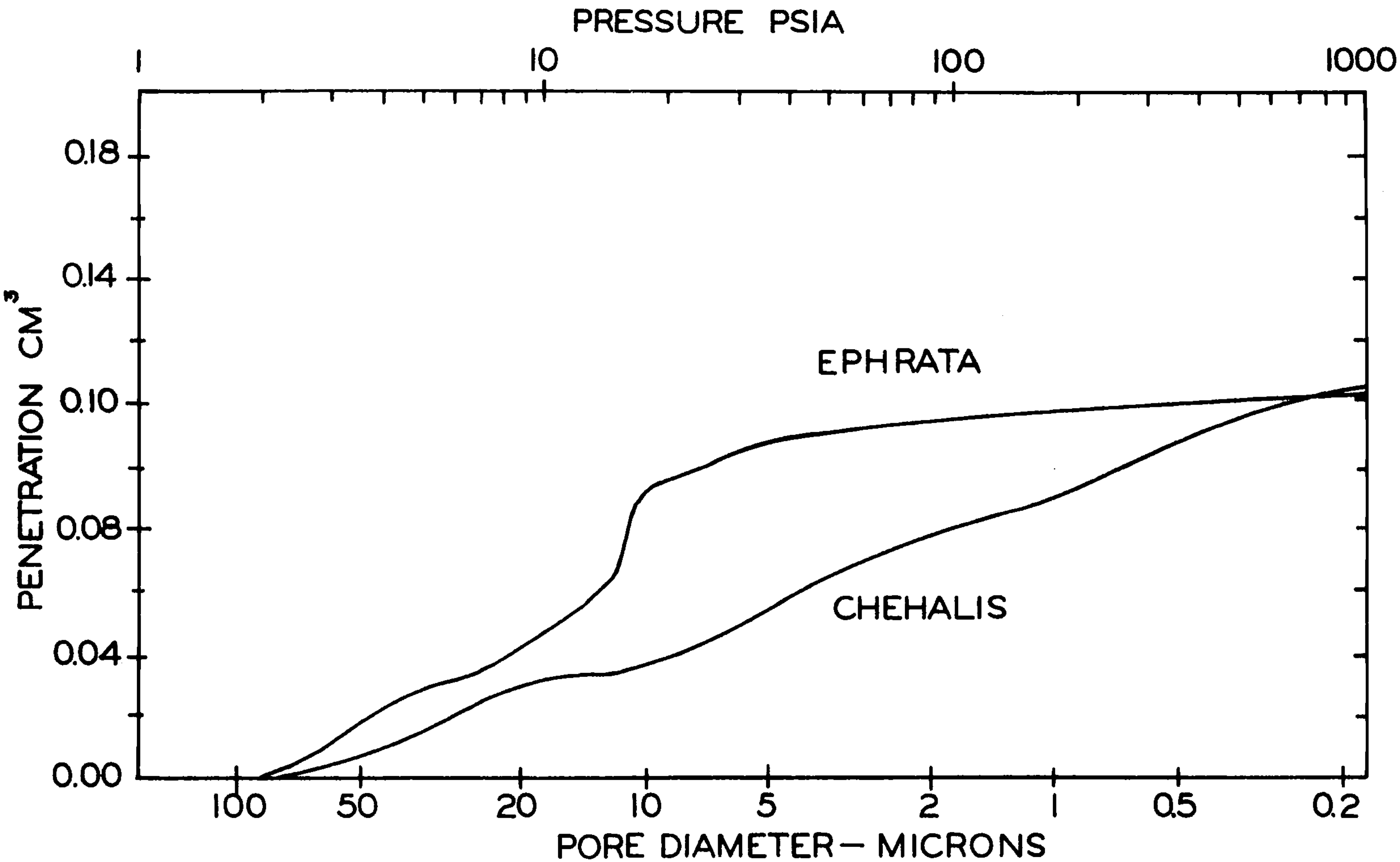

Figure 2. Pore size distribution obtained by mercury intrusion for Ephrata loamy sand and Chehalis loam. The graphs shown represent pore size accumulation curves. The actual pore space in a given pore size increment can be obtained from the ordinate which shows penetration in cm^3 of mercury.

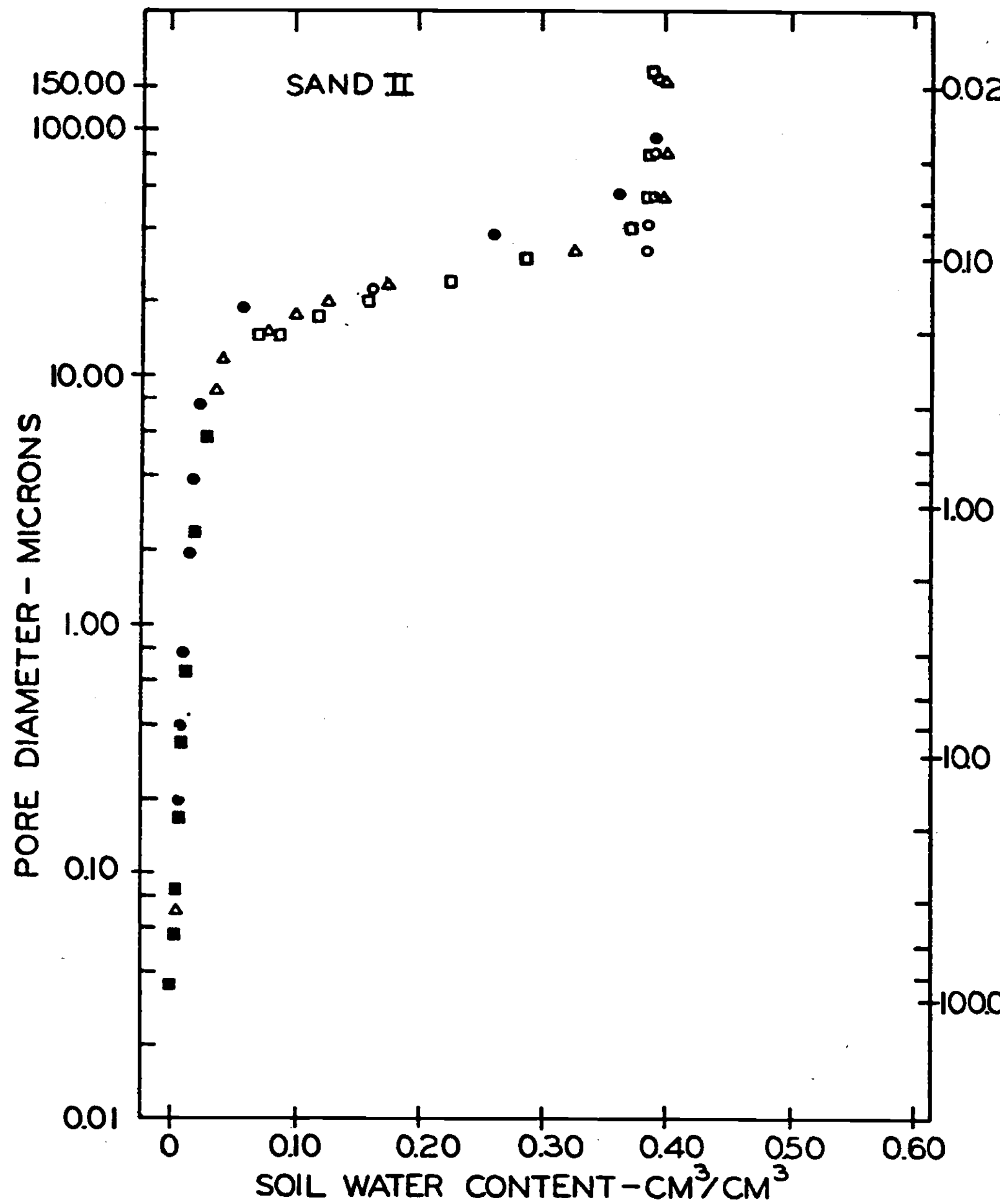

Figure 3. Soil water characteristic curves determined by mercury intrusion (△, □, and ■) and by the pressure plate apparatus (●). The data obtained by mercury intrusion represent three samples showing the reproducibility of this technique. These data were collected during part of one day. About one week of work, distributed over a one month period, was required to obtain the 9 pressure plate points. Results from the two procedures agreed quite well.

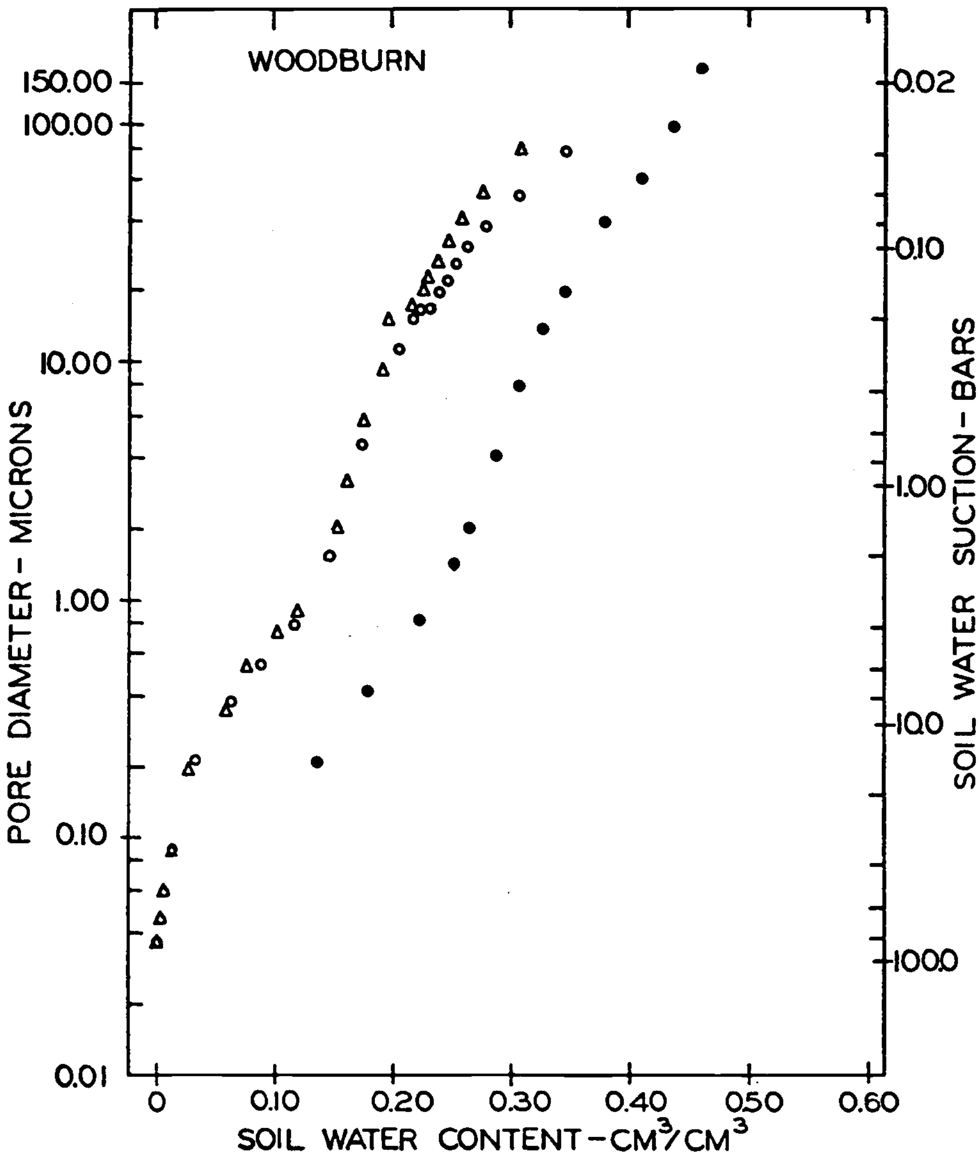

Figure 4. Soil water characteristic curves determined by mercury intrusion (Δ, O) and by the pressure plate apparatus (●). The data obtained by mercury intrusion represent three samples showing the reproducibility of this technique. These data were collected during part of one day. About one week of work, distributed over a one month period, was required to obtain the pressure plate points. Results from the two procedures did not agree. The two curves can be made to coincide by transposing the mercury intrusion curve to the right. The degree of transposition required is a function of the clay content of the soil (see Figure 5).

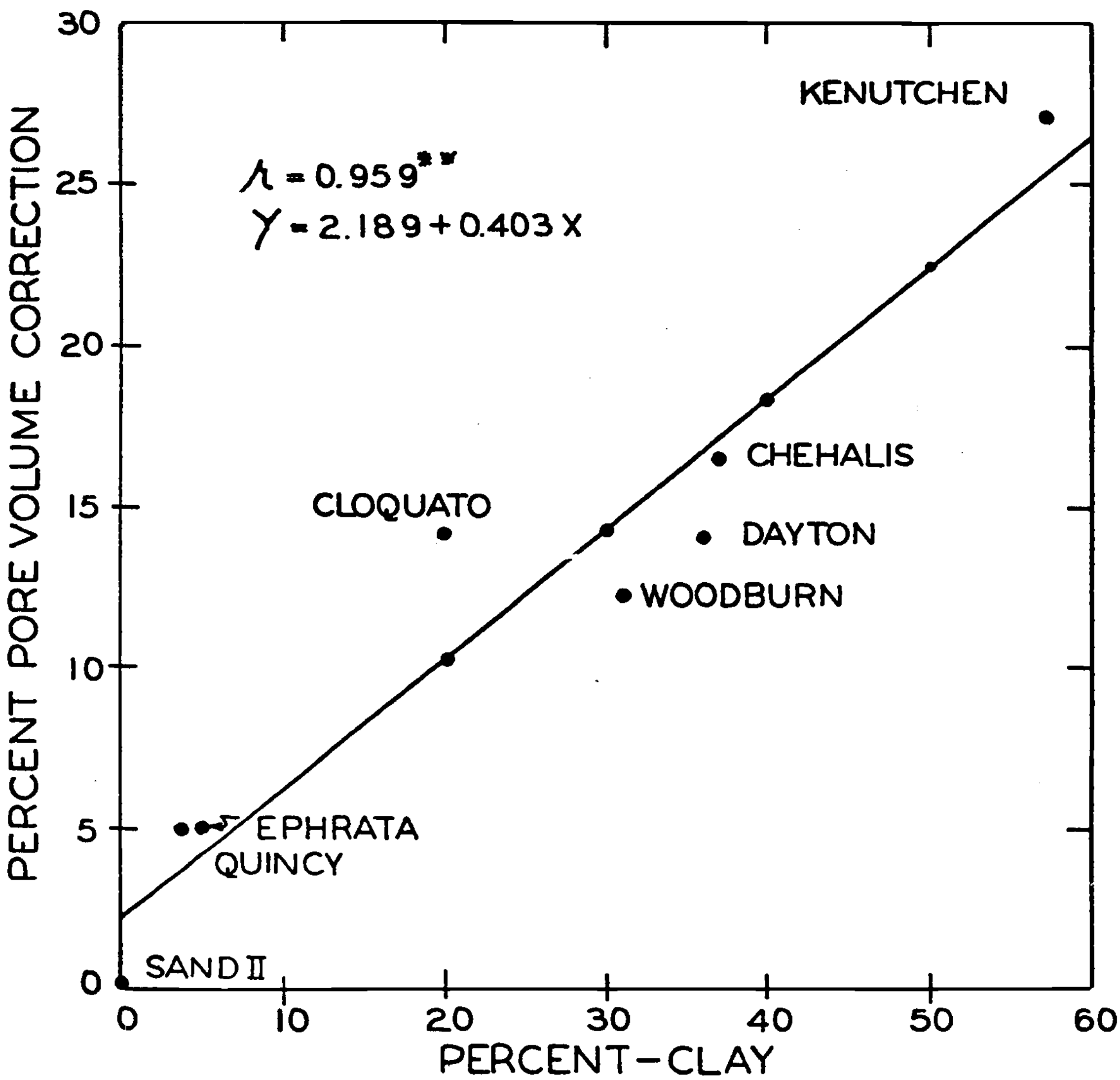

Figure 5. Degree of transposition required to make the mercury intrusion data coincide with the pressure plate data in percent pore volume as a function of the clay content of the soil.

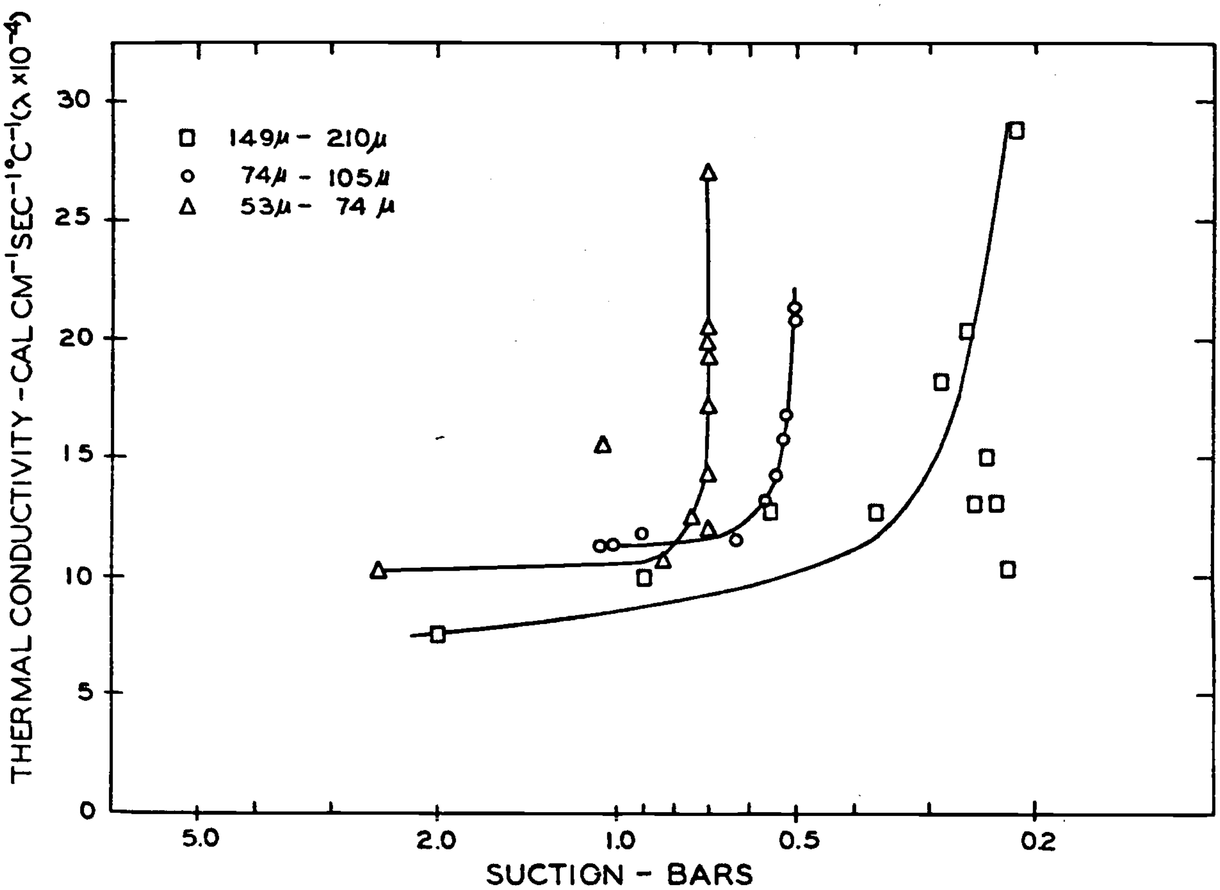

Figure 6. Thermal conductivity of three size classes of glass beads as a function of water suction. The rapid decrease of the thermal conductivity of the largest size class at about 0.2 bars indicates that most of the water drains at this suction. To remove water from the smaller size classes progressively higher suctions are required.

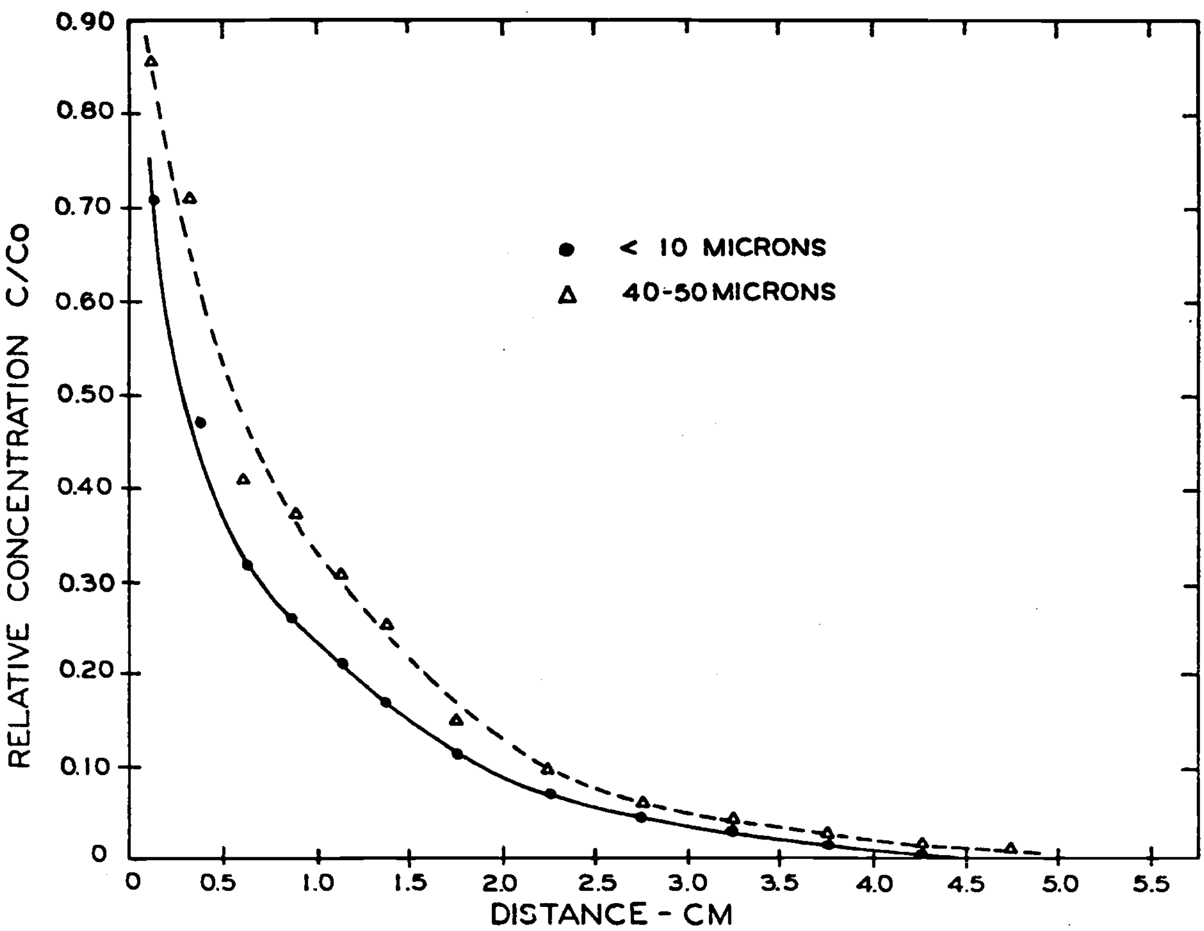

Figure 7. Distribution of 2-4,D in columns made up of glass beads. The concentration at the face of the columns was maintained constant. The graphs show the influence of pore size on diffusion. The rate of advance decreased as pore size decreased. Total pore space was the same in all samples. Diffusion coefficients calculated from these curves allow an evaluation of the equation stated in the text.