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A Physicoempirical Model to Predict the Soil Moisture Characteristic from Particle-Size Distribution and Bulk Density Data[1]

LALIT M. ARYA AND JACK F. PARIS[2]

ABSTRACT

A model to predict the moisture characteristic of a soil from its particle-size distribution, bulk density, and particle density parameters is presented. The model first translates a particle-size distribution into a pore-size distribution. Then, the cumulative pore volumes corresponding to progressively increasing pore radii are divided by the sample bulk volume to give the volumetric water contents, and the pore radii are converted to equivalent soil water pressures using the equation of capillarity.

To compute the pore volumes and the pore radii, the particle-size distribution curve is divided into a number of segments. The solid mass in each segment is assumed to form a matrix with a bulk density equal to that of a natural-structure sample. For a unit of sample mass, an equivalent pore volume for each segment is computed from $V_{v_i} = (W_i/\varrho_p)e$ and the corresponding pore radius from:

$$r_i = R_i[4en_i^{(1-\alpha)}/6]^{1/2},$$

where V_{v_i} is the pore volume, W_i is the solid mass, ϱ_p is the particle density, e is the void ratio, r_i is the mean pore radius, R_i is the mean particle radius, n_i is the number of particles, and α is an empirical constant ranging in value from 1.35 to 1.40. The formulation for the pore radius is based on spherical particles and cylindrical pores.

Model predictions for several soil materials show close agreement with the experimental data.

Additional Index Words: pore radius, pore-size distribution, capillarity.

Arya, L. M., and J. F. Paris. 1981. A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. Soil Sci. Soc. Am. J. 45:1023-1030.

A QUANTITATIVE ANALYSIS of soil water processes depends on the availability of data on two fundamental soil hydrologic properties. These are (i) the relationship of soil water pressure to soil water content, and (ii) the relationship of hydraulic conductivity to either the soil water pressure or the soil water content. The former, commonly referred to as the soil moisture characteristic, is not only used in prediction of soil moisture changes and hydraulic potential gradients in a flow system, but it also constitutes an input for some hydraulic conductivity models (e.g., Childs and Collis-George, 1950; Marshall, 1958; Brooks and Corey, 1964; Jackson, 1972; Mualem, 1976).

Laboratory determination of the soil moisture characteristic involves desorption of an initially saturated soil sample to a prespecified pressure and then determination of its equilibrium water content (Richards, 1965). The field method involves in situ measurements of soil water pressure by tensiometers installed at depths of interest and of water content by gravimetric sampling or neutron or gamma attenuation techniques. Since sample environment (confinement and overburden) are not represented in laboratory procedures, laboratory data may not always agree with field data. The disagreement between the two types of data appears more pronounced at high water contents (e.g., Arya, 1975; Arya et al., 1975; Nagpal and deVries, 1976).

Both the laboratory and the field procedures employed in determination of the soil moisture characteristic are tedious, time consuming, and expensive. Thus, when a solution to hydrologic problems spanning large areas (e.g., a watershed or an agricultural region) comprised of a variety of soils is sought, the economic feasibility of experimental efforts needs to be considered. In view of the spatial variability of soil hydrologic properties (e.g., Nielsen et al., 1973; Coelho, 1974; Keisling, 1974; Peck et al., 1977; Philip, 1980; Russo and Bresler, 1980), the cost of adequate efforts may be prohibitive.

An alternative to the experimental approach is the prediction of hydrologic properties from routinely measured textural and structural soil properties. The simplest of the predictive approaches consists of relating water contents at specified soil water pressures to soil texture, organic matter, and/or bulk density, using multiple regression analysis (e.g., Jamison and Kroth, 1958; Salter et al., 1966; Hall et al., 1977; Gupta and Larson, 1979). Other approaches for the estimation of the soil moisture characteristic (e.g., Brooks and Corey, 1964; Visser, 1966; Gardner et al., 1970; Rogowski, 1971; Ghosh, 1976; Clapp and Hornberger, 1978) propose some form of a power curve with constants that must be evaluated empirically. Additionally, a knowledge of part of the soil moisture characteristic is required for some models (e.g., pressure and water content at air-entry point and water content at −15 bar pressure in the Rogowski model). Although both the regression equations and the power curve formulations are being used in predicting the moisture retention data, both lack the physical basis to account for the effects of texture and packing characteristic of the medium. Moreover, failure to trace a realistic shape of the curve, particularly in the wet range, remains a weakness inherent in both the approaches.

We propose a physicoempiricial approach to derive the moisture characteristic of a soil from its particle-size distribution and bulk density in the natural state of packing.

MODEL DESCRIPTION

The idea for the proposed model emerged from observations of similarities between the shapes of particle-size distribution and soil moisture characteristic curves. We compared the moisture characteristic of a number of soil materials against their particle-size distribution curves and found the two curves to be very similar in shape. The question is whether or not an

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objective procedure can be used to translate a particle-size distribution curve into a moisture characteristic curve. Recognizing that the soil moisture characteristic is essentially a pore-size distribution curve, the task clearly involves finding a pore volume and a representative pore radius corresponding to each particle-size fraction on the soil particle-size distribution curve. What follows is our derivation of soil moisture characteristic curve from the particle-size distribution data and the packing density of the natural soil sample.

Pore Volume and Volumetric Water Content

We divide the cumulative particle-size distribution curve into n fractions and then reassemble the solid mass to form a natural-structure sample. In doing so, we imagine that particles in each size fraction pack in a discrete domain and that, when all the domains are assembled together, the resulting assemblage has a bulk density measured on a natural-structure sample. This requires us to assume that the bulk density of the natural-structure sample applies to the assemblages formed by each of the n fractions uniformly. We recognize, of course, that in a natural sample, particles are not packed in discrete domains consisting of uniform-size particles; they are more or less randomly distributed. But since our interest is in a pore volume attributable to the particles in a given size fraction, the assumption made above does not pose an inexplicable problem.

We now compute the pore volume associated with each size fraction:

$$V_{v_i} = (W_i/\varrho_p)e; \; i = 1, 2, \ldots, n, \qquad [1]$$

where V_{v_i} is the pore volume per unit sample mass associated with the solid particles in the ith particle-size range, W_i is the solid mass per unit sample mass in the ith particle-size range, ϱ_p is the particle density, and e is the void ratio. The values of W_i are obtained from the plots of particle-size distribution (see Fig. 1 for an example). The differences in cumulative percentages corresponding to successive particle sizes divided by 100 result in values of W_i such that the sum of all W_i is unity. The void ratio e is given by:

$$e = (\varrho_p - \varrho_b)/\varrho_b, \qquad [2]$$

where ϱ_b is the measured bulk density of the natural-structure sample.

The pore volumes V_{v_i} generated by each size fraction are progressively accumulated and considered filled with water. The volumetric water content is then computed:

$$\theta_{v_i} = \sum_{j=1}^{j=i} V_{v_j}/V_b; \qquad i = 1, 2, \ldots, n, \qquad [3]$$

where θ_{v_i} is the volumetric water content represented by a pore volume for which the largest size pore corresponds to the upper limit of the ith particle-size range, and V_b is the sample bulk volume per unit sample mass given by:

$$V_b = \sum_{i=1}^{i=n} W_i/\varrho_b = 1/\varrho_b; \qquad i = 1, 2, \ldots, n. \qquad [4]$$

An average volumetric water content corresponding to the midpoint of a given particle-size range is given approximately (if size intervals are small) by:

$$\theta^*_{v_i} = (\theta_{v_i} + \theta_{v_{i+1}})/2, \qquad [5]$$

where $\theta^*_{v_i}$ is the average volumetric water content represented by a pore volume for which the largest size pore corresponds to the midpoint of the ith particle-size range.

Particle Size and Pore Radius

In addition to the assumption made earlier that the solid fraction in each particle-size range can be assembled into a discrete domain with a bulk density equal to that of the natural-structure sample, we assume (i) that the solid volume in any given assemblage can be approximated as that of uniform-size spheres defined by the mean particle radius for the fraction, and (ii) that the volume of the resulting pores can be approximated as that of uniform-size cylindrical capillary tubes whose radii are related to the mean particle radius for the fraction. With these assumptions, we formulate the relationship between pore and particle radii as follows.

If the solid mass in the ith particle-range is represented by n_i spherical particles and if the entire pore volume formed by the

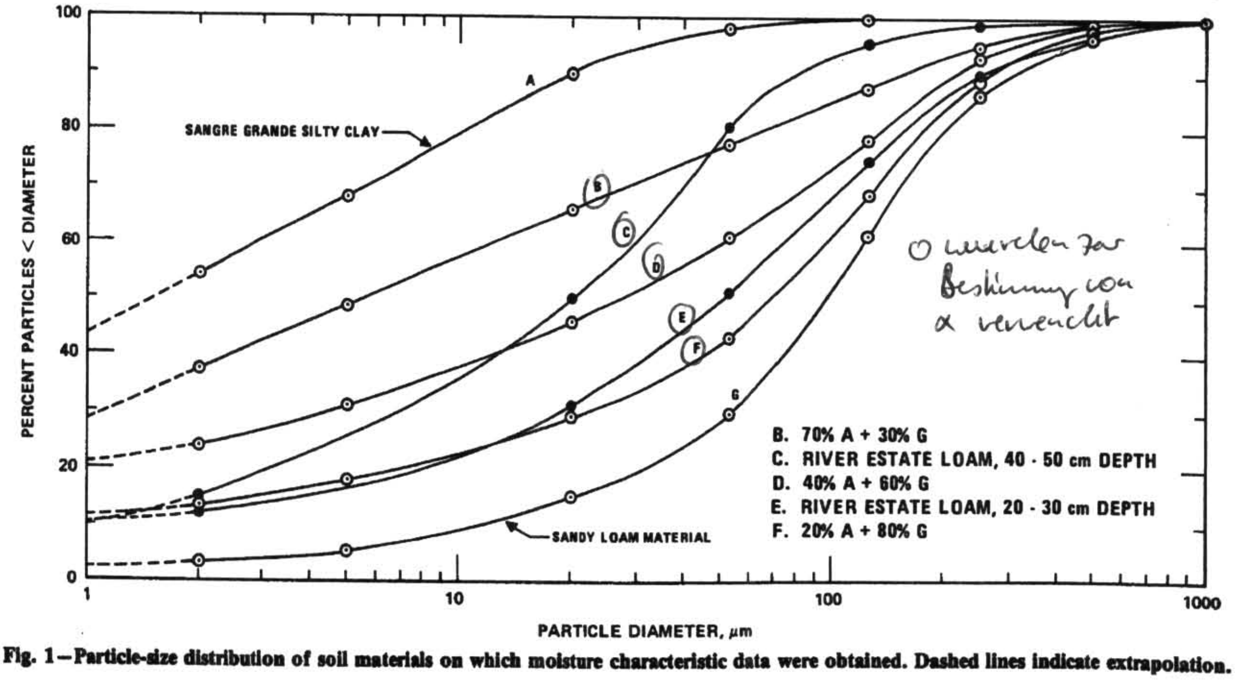

Fig. 1—Particle-size distribution of soil materials on which moisture characteristic data were obtained. Dashed lines indicate extrapolation.

assemblage of particles in that range is represented by a single cylindrical pore, then:

$$V_{p_i} = n_i 4\pi R_i^3/3 = W_i/\varrho_p, \quad [6]$$

and

$$V_{v_i} = \pi r_i^2 h_i = (W_i/\varrho_p)e, \quad [7]$$

where V_{p_i} is the total solid volume in the assemblage, R_i is the mean particle radius, r_i is the mean pore radius, and h_i is the total pore length.

Dividing Eq. [7] by Eq. [6] gives:

$$r_i^2/R_i^3 = 4n_i e/3h_i. \quad [8]$$

Berechnung der Anzahl der Röhren mit einer best. Länge

For a given assemblage of particles, we propose to approximate the pore length as the number of particles that lie along the pore path times the length contributed by each particle. Thus, in a cubic close-packed assemblage of uniform-size spherical particles, the total pore length will equal $n_i 2R_i$. In a natural soil material, however, the pore length will depend on actual particle shapes, sizes, and orientations. Given that the actual soil particles are nonspherical, we assume that each particle contributes a length that is greater than the diameter of an equivalent sphere. As a result, the number of spherical particles with radius R_i required to track the total pore length in a natural soil material will exceed n_i. Let the number of particles required be n_i^α, where α is > 1. The total pore length, h_i, will then equal $n_i^\alpha 2R_i$.

Substitution for h_i in Eq. [8] gives:

Der Wert α ist der Knackpunkt

$$r_i = R_i[4en_i^{(1-\alpha)}/6]^{1/2}. \quad [9]$$

The value of n_i in Eq. [9] can be obtained from Eq. [6], and α is to be determined empirically.

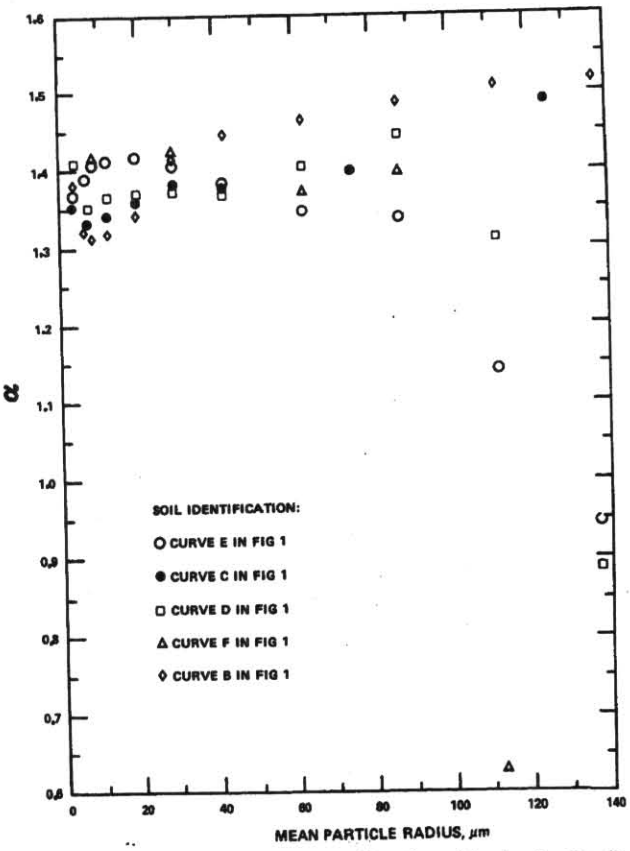

Fig. 2—Model parameter α as a function of particle size for 5 soil materials.

Pore Radius and Soil Water Pressure

Once the pore radii are obtained, the equivalent soil water pressure can be obtained from the familiar equation of capillarity,

$$\psi_i = 2\gamma \cos \Theta/\varrho_w g r_i, \quad [10]$$

where ψ_i is the soil water pressure, γ is the surface tension of water, Θ is the contact angle, ϱ_w is the density of water, g is the acceleration due to gravity, and r_i is the pore radius. Surface tension and density of water are temperature dependent, while the contact angle may vary depending on organic content of the soil. For the purpose of this paper, however, we will assume a temperature of 25° C and a contact angle of 0°. Where adequate information on temperature and contact angle is available, appropriate adjustments may be made.

MATERIALS AND METHODS

Particle-size distribution, bulk density, and soil moisture characteristic data used in the present study were obtained by the senior author while at the Caribbean Agricultural Research and Development Institute and the University of the West Indies, Trinidad. The objectives of the studies from which these data originated ranged from characterization of the physical properties of agriculturally important soils of Trinidad to structural improvement of swelling clay soils by incorporating in them coarse sandy materials.

Data were obtained on two types of materials: (i) natural-structure clods from several depths in a River Estate loam soil profile; and (ii) mixtures of Sangre Grande silty clay, a swelling soil and a sandy loam material collected from a river bank. The soil mixtures were prepared by combining < 2-mm air-dry Sangre Grande silty clay and the sandy loam material in varying proportions on a weight basis.

Particle-Size Distribution Data

For both the soil mixtures and the River Estate loam, particle-size analyses were carried out on < 2-mm material by the pipette method as described by Day (1965). The sand was fractionated by dry-sieving. At the time the River Estate loam was analyzed, unavailability of required sizes of sieves limited the number of fractions into which the sand fractions could be separated. Particle-size distribution data for the Sangre Grande silty clay, sandy loam material, three soil mixtures, and samples from two depths in the River Estate loam profile are plotted in Fig. 1. The dotted lines in this figure indicate extrapolation, and the data points are means of three samples.

Bulk Density Data

For the River Estate loam soil, bulk density was measured on natural-structure clods by a method proposed by Brasher et al. (1966). Five to six clods, each 200 to 300 g in size, were used for each depth.

Air-dry mixtures of Sangre Grande silty clay and the sandy loam material were filled in rigid plastic cups (about 500 ml in volume with 8.5-cm. i.d. at the top), each with holes and a filter paper in the bottom. To ensure uniformity, the cups were tapped and vibrated while being filled with the soil mixture. All cups were filled to the same height regardless of the soil weight. The oven-dry weight of the soil material in each cup was calculated from the air-dry water contents determined on representative samples from each of the mixtures. Thirty-six cups for each soil mixture were prepared and placed in troughs in which the free water level was raised slowly until the soil was saturated. A couple of days later, the free water from the troughs was removed, and the soil material in the plastic cups was allowed to drain and partially dry. The saturation process was repeated, and the samples were again allowed to drain.

After the saturation and drainage of free water, samples were set on laboratory benches and allowed to dry slowly. As the samples dried, their bulk densities were determined as a function of water content. At the initial stages of drying, soil volume was calculated from the demensions of the soil blocks in the plastic cups. As the drying progressed and cracks developed, soil sections between the cracks were separated and their bulk densities were determined by the technique used for the River Estate loam natural-structure clods. A small portion from each section was oven-dried to obtain water content.

Maximum shrinkage was exhibited by the Sangre Grande silty clay with no sandy loam material added. Shrinkage decreased as the proportion of sandy loam material increased. Data used in the present study are from the soil mixtures that did not show perceptible volume changes upon drying.

Soil Moisture Characteristic Data

Initial determinations made on River Estate loam natural clods using a pressure plate apparatus (Richards, 1965) showed variable water contents at high soil water pressures and often greater than the maximum porosity based on bulk density measurements. Therefore, in order to obtain more reliable data, in situ measurement of the soil moisture characteristic was considered necessary. In a field plot adjacent to the sampling pit from which the natural-structure clods were obtained, tensiometers were installed at 10-cm depth intervals down to a depth of 120 cm. The plot was irrigated heavily, and the soil was allowed to dry. With a system of mercury manometers connected to the tensiometers via polyvinyl tubing, the soil water pressure was recorded as a function of depth and time. Water content was obtained by periodic gravimetric sampling. Data thus obtained were limited to about −300 to −500 cm pressure. The remainder of the soil moisture characteristic (up to −15,000 cm pressure) was determined on natural-structure clods using the pressure plate apparatus.

For the soil mixtures also, a tensiometric measurement of moisture characteristic was considered necessary. Samples were prepared in the same way as for the bulk density measurements except that the plastic cups used were of a liter size with a 12-cm i.d. at the top. For measurement of soil water pressure, porous ceramic cups (6.5 cm in length, 0.67-cm o.d., and 0.2-cm wall thickness) connected to mercury manometers via thin polyvinyl tubing were installed vertically in the center of each plastic cup. The wet soil in the cups was allowed to dry slowly, and soil water pressure for each successive increment of drying was recorded. During the drying process, after a small increment of water loss, the cups were covered with a lid until the mercury heights in the manometers became stable. Only the stable mercury heights were used in computing the pressures. All measurements of soil water pressure were referred to the midpoint along the length of the porous ceramic cup. Water content corresponding to each soil water pressure was obtained by weighing. A connector in the polyvinyl tubing about 20 cm from the cup facilitated disconnecting and reconnecting of the cups and the manometer system. When the limit

Anpassung von α

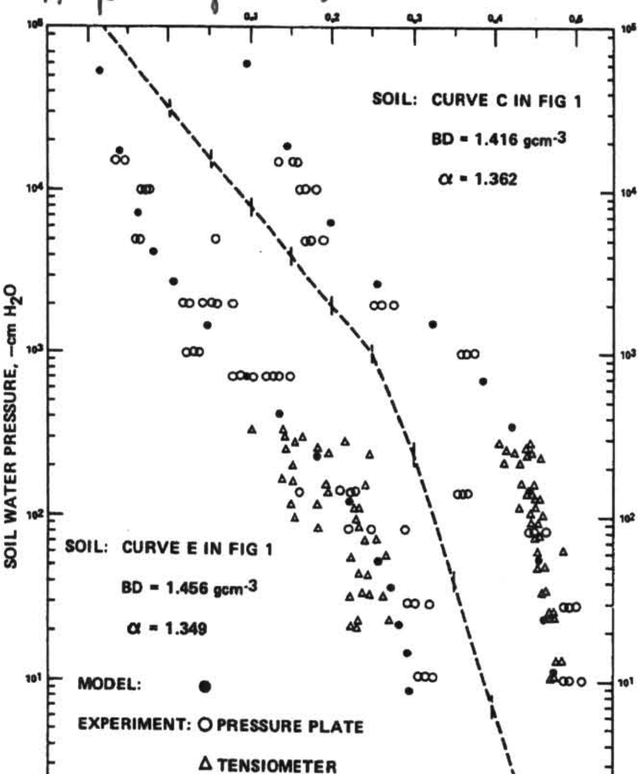

Fig. 3.—Measured and calculated soil moisture characteristics, bulk density, and best-fit α for soil materials represented by particle-size distribution curves *C* and *E* in Fig. 1.

Anpassung von α

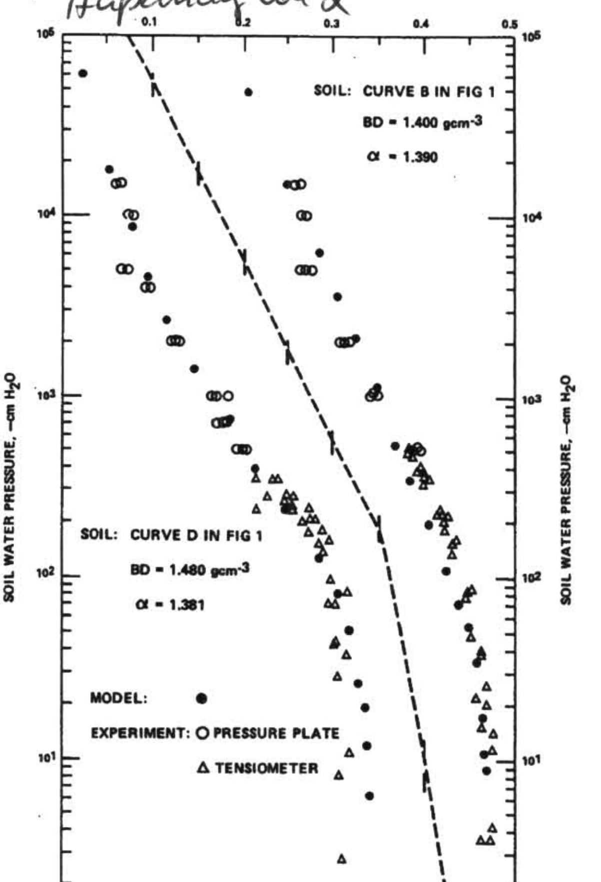

Fig. 4—Measured and calculated soil moisture characteristics, bulk density, and best-fit α for soil materials represented by particle-size distribution curves *B* and *D* in Fig. 1.

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Anpassung von α

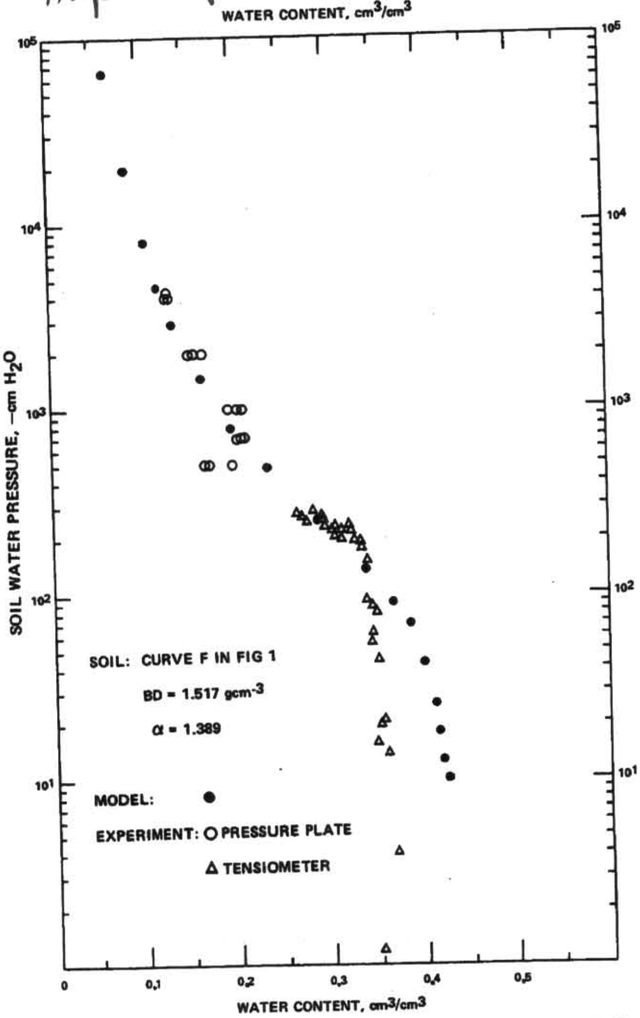

Fig. 5—Measured and calculated soil moisture characteristics, bulk density, and best-fit α for soil material represented by curve F in Fig. 1.

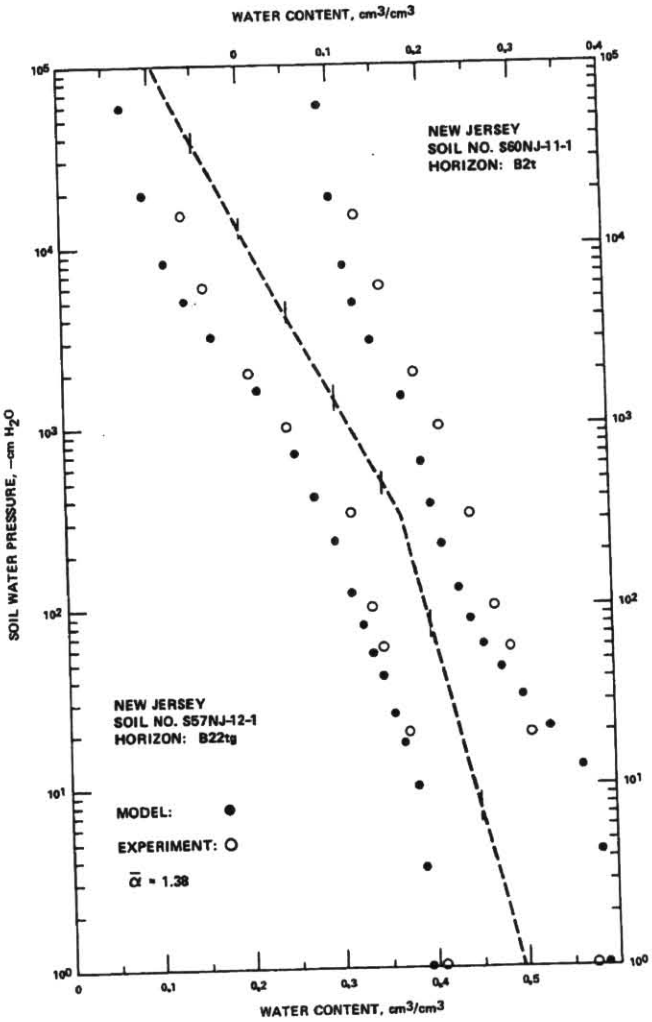

Fig. 6—A comparison between measured and predicted soil moisture characteristics for two New Jersey soils. Model inputs and measured moisture characteristics data are taken from Soil Survey Investigations Rep. no. 26 (1974).

of tensiometric meaurements (about −500 cm pressure) was reached, the soil block in each cup was cut into a number of clods. These clods were saturated and desorbed to several equilibrium pressures (up to −15,000 cm) on a pressure plate apparatus.

RESULTS AND DISCUSSION

Berechnung von α aus 5 UGV (B, C, D, F, E)

The nature of the parameter α in Eq. [9] was examined by computing its value as a function of particle size for five of the soil materials shown in Fig. 1. For any given soil, the computed water contents based on Eq. [1] through [5] were translated into soil water pressures using the measured moisture characteristic curve. These pressure values were then converted to equivalent pore radii using Eq. [10]. The pore radii were substituted in Eq. [9], which was then solved for α. The values of α thus computed are plotted as a function of mean particle radius in Fig. 2. Data show that for particle radii from about 4 μm to about 100 μm the value of α does not change substantially. Furthermore, over this range of particle sizes, the values of α for five texturally different soil materials lie within a narrow range from about 1.31 to about 1.43. For the particles larger than a 100-μm radius, there appears to be a tendency for α to drop sharply with an increase in particle size. Since the computed data points are few and scattered, however, a conclusion cannot be drawn. In addition to the data in Fig. 2, an overall best-fit value of α for each of the soils was also calculated by an iterative procedure that minimized the sums of $|\log \psi_{meas} - \log \psi_{calc}|$. For the five soils, the best-fit values of α ranged from 1.35 to 1.39.

The measured and the model-predicted moisture characteristics based on the best-fit values of α for the five soil materials are shown in Fig. 3, 4, and 5. The best-fit value of α and the measured bulk density and particle-size distribution as inputs to the model are indicated in each figure.

Based on the values of α shown in Fig. 2 and those obtained by minimizing the sums of $|\log \psi_{meas} - \log \psi_{calc}|$, a value of 1.38 was considered as the best estimate of α. Using this value of α, the model was tested on six New Jersey soils (Soil Survey Investigations Report no. 26, 1974), two soils from Trinidad [Böehr-

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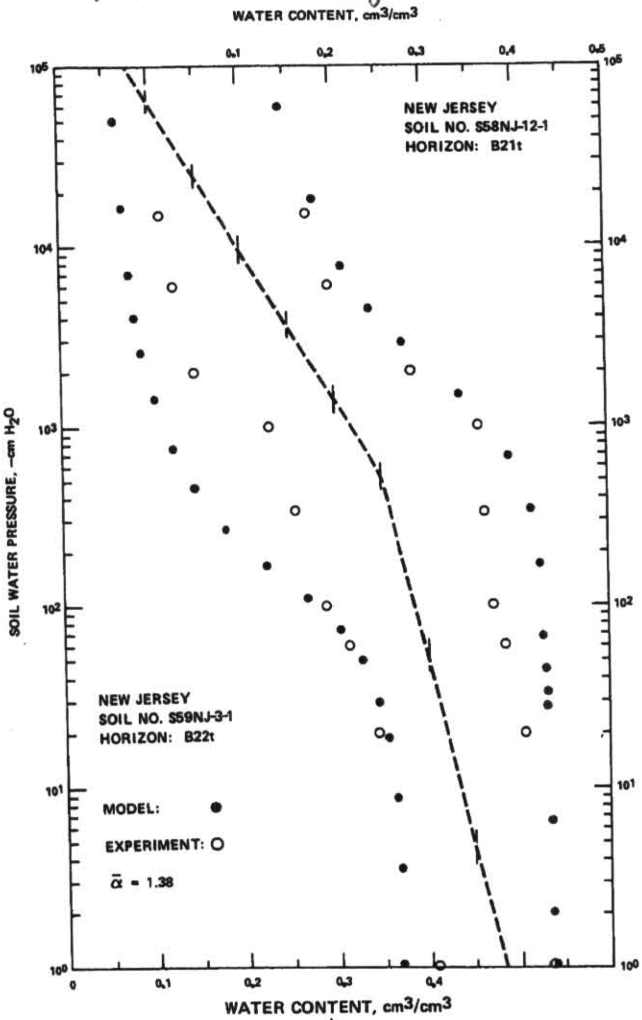

Fig. 7—A comparison between measured and predicted soil moisture characteristics for two New Jersey soils. Model inputs and measured moisture characteristics data are taken from Soil Survey Investigations Rep. no. 26 (1974).

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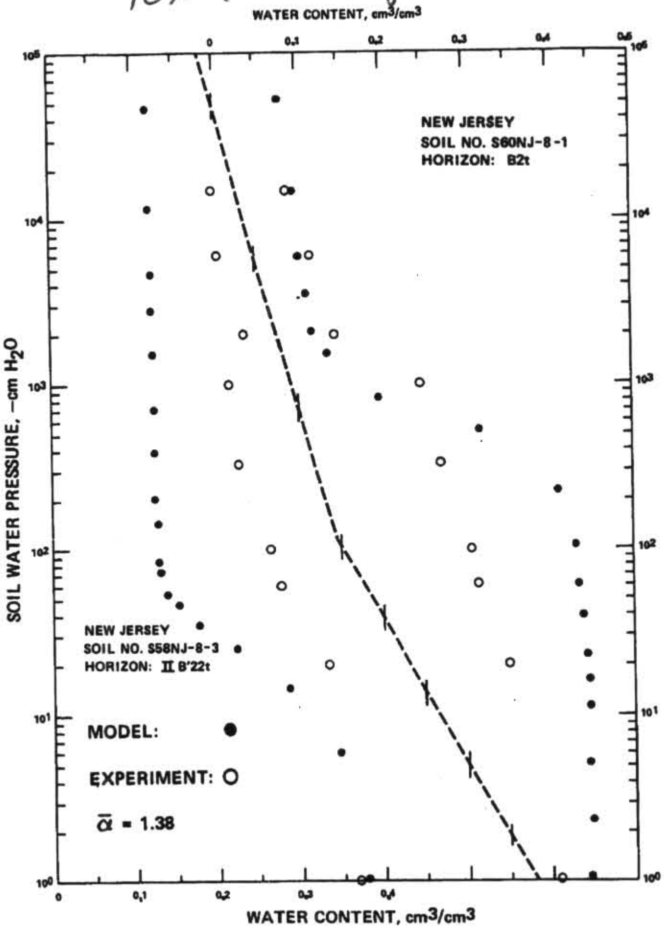

Fig. 8—A comparison between measured and predicted soil moisture characteristics for two New Jersey soils. Model inputs and measured moisture characteristics data are taken from Soil Survey Investigations Rep. no. 26 (1974).

inger (1975)[3], one soil from Georgia (Long et al., 1969), and one soil mixture consisting of 50% each of the soils A and G in Fig. 1. The results of the test are shown in Fig. 6 through 10. For several soils, the predicted moisture characteristics data are in close agreement with the measured data (see Fig. 6, 9, and 10). For some others, the agreement between the two types of data appears somewhat marginal (Fig. 7). An example of a rather wide disagreement between the predicted and the measured data is shown in Fig. 8. In some cases, the agreement between the two types of data appears to vary from one part of the moisture characteristic curve to another (see Fig. 7 for an example); there is, however, no consistent pattern. The close agreement between the predicted and the measured data for several soils shows that a reasonable soil moisture characteristic can be derived from particle-size distribution and bulk density measurements. The disagreements that exist could be real, suggesting limitations in the model under certain circumstances. Or they could be the result of uncertainties in the inputs and the measured moisture characteristic data.

Behauptung

The proposed model is based on the assertion that the size of the particles and the density to which they are packed are the primary determinants of the pore size. This, however, is not the entire case. Aggregation of primary particles into secondary and tertiary particles, root channels, and microcracks would account for a fraction of the pore volume with radii not determined by the distribution of primary particles. It is, however, the relative abundance of such pores that would determine the extent to which the model predictions would deviate from reality. Large deviations, therefore, should be expected—mainly in the case of surface soil materials where aggregation, cracking, and root effects may be pronounced. Similarly, for soil materials which exhibit significant volume change upon wetting and drying, model predictions of the moisture characteristics will not be accurate. The problems of hysteresis are also beyond the scope of the present model.

Einschränkungen: Wurzel, Aggregation, Makroporen, Risse usw. Hysterese

Data utilized in developing the model parameter α and those used in testing the predictive ability of the model were obtained on soil materials which are all known or believed to be nonswelling and with a low

[3] I. A. Böehringer. 1975. Variation of structure and water conducting properties of Cunupia silty clay. M.S. Thesis, Univ. of the West Indies, Trinidad.

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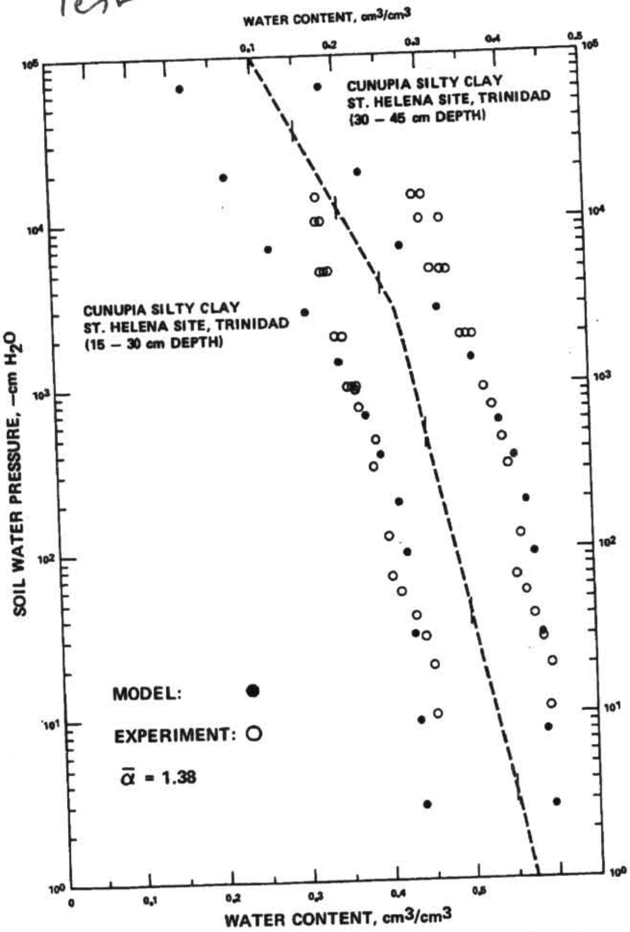

Fig. 9—A comparison between measured and predicted soil moisture characteristics for two Trinidad soils. Model inputs and measured moisture characteristics data are taken from Böehringer.[3]

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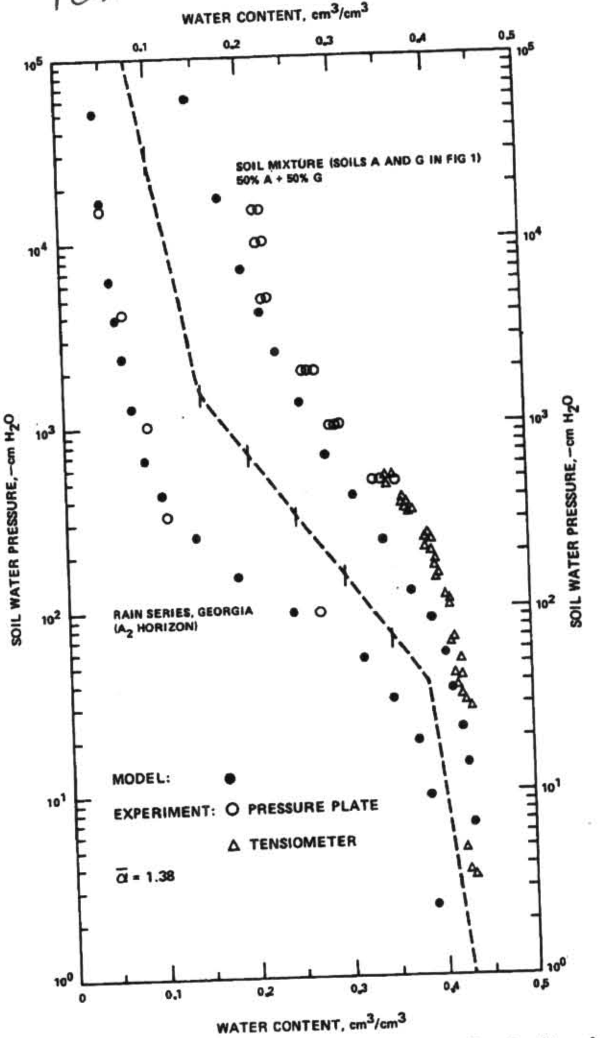

Fig. 10—A comparison between measured and predicted soil moisture characteristics for (*i*) a Georgia soil (model inputs and measured moisture characteristics data are taken from Long et al., 1969), and (*ii*) a soil mixture consisting of 50% each of the soils *A* and *G* in Fig. 1.

degree of aggregation. Yet, model predictions of some of the measured data were poor (see Fig. 7 and 8 for examples). It is probable that uncertainties in the inputs and the measured moisture characteristics have contributed to the observed disparities. Uncertainties of $\pm 5\%$ in the particle-size distribution and ± 0.1 g/cm³ in the bulk density data are not uncommon (e.g., Coelho, 1974; Keisling, 1974; Alexander, 1980). Additionally, large errors in the measurement of soil moisture characteristics may arise from changes in soil structure (e.g., Croney and Coleman, 1954) during sample preparation, treatment, and handling. The effect is more pronounced in the wet range where volume expansion and closure of the pores due to puddling during the initial saturation are both likely. In procedures where a pressure plate apparatus is used, shrinkage of soil materials in the dry range may lead to poor contact and errors in the measurement of equilibrium water content. An incomplete saturation of the experimental soil material may also cause a discrepancy between the predicted and the measured data. The presence of trapped air and/or hydrophobic constituents (e.g., Debano, 1971; Scholl, 1971) may cause the actual saturation values to be less than would be expected from the total pore space. The model, on the other hand, equates the maximum water content to the porosity computed from the bulk and particle density data and assumes a complete saturation when the largest pores are included. Disagreements, however, between the actual and theoretical porosities (e.g., Lin, 1971) may introduce errors in the model's estimate of the maximum water content.

Thus, in view of the uncertainties in the measurements of soil moisture characteristics and input data, complete agreement between the model predictions and the experimental data would appear somewhat fortuitous. What seems important is the shape of the soil moisture characteristic curve, particularly towards the saturated end. The shape of the model-predicted curve is similar to that of the input particle-size distribution and matches well with the measured curves (see Fig. 3 to 5, 9, and 10). In previous attempts (e.g., Brooks and Corey, 1964; Rogowski, 1971, 1972), prediction of the shape of the soil moisture characteristic curve at high pressures has been difficult and largely ignored. Mualem (1976) speculates that neglecting the soil moisture characteristic curve near saturation might improve the estimates of hydraulic conductivity. Others (e.g., Rogowski, 1971; Clapp and Hornberger, 1978) attempt to define this portion of the curve by equations which are different from those formulated for the drier portion of the moisture characteristic. Whether or not an improved overall prediction is obtained remains uncertain (e.g., Brakensiek, 1979). In comparison with other modeling efforts, the shape of the soil moisture characteristic curve near saturation predicted by our model is very nearly identical to that obtained by tensiometric measurements. It should also be noted that, while experimental data available in the literature are generally limited to −15 bar pressure, our model predicts data in the drier range where measurements are difficult.

Based on the tests we have made (see Fig. 6 through 10) and considering the uncertainties in the measurements, the overall predictive ability of the proposed model would appear reasonable. The only input data required are particle-size distribution and bulk density. These data are readily available in the soil survey reports. Particle-size distributions used in the present study were constructed from five to eight data points; however, a more detailed fractionation of the soil would be desirable. For aggregated soil materials, aggregate-size distribution in addition to particle-size distribution may be required for improved predictions. Further testing of the model and evaluation of the effects of particle-size distribution, packing density, organic matter, and aggregation should reveal the weaknesses in the model and indicate the nature of additional information needed for improvement.

ACKNOWLEDGMENTS

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ARYA, L. M., PARIS, J. F. (1981): A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. Soil Science Society of America Journal, Vol. 45, S. 1023-1030.
Kennung: pF_A_P_1981

Der Artikel befaßt sich mit der Bestimmung/Abschätzung der Saugspannungsbeziehung aus der KGV unter Berücksichtigung der Trockendichte. Hier wurde bereits die Ähnlichkeit zwischen der KGV und der pF-Kurve erkannt und man schloß, daß in erster Linie die pF-Kurve eine Verteilungsfunktion der Porengrößen darstellt.

Die KGV wird in n gleichen Fraktionen aufgeteilt und für jede dieser Fraktionen wird ein entsprechendes Porenvolumen ermittelt. Hierbei wird davon ausgegangen, daß man einen Erdstoff in diskrete Bereiche gleicher Korngröße zerlegen und diese mit einer gleichen Trockendichte des natürliche Bodens wieder zusammenfügen kann. Aus den Porenvolumina für entsprechende Korngrößen können die volumetrischen Wassergehalte und mittlere Wassergehalte für jede Fraktion ermittelt werden.

Unter der Annahme gleicher mittlerer Korngrößen für jede Fraktion werden die Poren als gleichförmige zylindrische Röhren angenähert, deren Durchmesser abhängig ist von dem jeweiligen mittleren Korndurchmesser der Fraktion. Über die Kenntnis der Anzahl der Körner in jeder Fraktion für ein gegebenen Durchmesser der Körner und ein gegebenes Feststoffvolumen wird eine Beziehung zwischen Radius der mittleren Korngröße und des entsprechenden Kapillardurchmessers ermittelt.

Um die Tatsache nicht runder Körner sowie deren unterschiedlicher Größen und Orientierung zu berücksichtigen wird ein empirisch zu ermittelnder Faktor eingeführt, aus welchem die mittlere Anzahl der Kapillaren ermittelt wird.

Dieser Faktor alpha wurde für 5 KGV angepaßt und ein mittlerer Faktor (von 1.35 bis 1.45) ermittelt. Der Vergleich zwischen berechneten und gemessenen pF-Kurven anderer Materialien waren sowohl gut als auch schlecht. Es hat sich gezeigt, daß man grundsätzlich die pF-Kurve aus der KGV ableiten kann, aber unter bestimmten Umständen ist dem vorgestellten Modell Grenzen gesetzt, wie z.B. die korrekte Abschätzung des Wertes alpha. Eine andere Unsicherheit besteht in der Qualität der Eingabeparameter (KGV, Trockendichte).

COMMENTS AND LETTERS TO THE EDITOR

Comments on "A Physicoempirical Model to Predict the Soil Moisture Characteristic from Particle-Size Distribution and Bulk Density Data"

Arya and Paris (1981) have recently related water retention curves to particle-size distributions. There is no doubt that the similarities between the shapes of the two curves justify their study. Indeed we have made a similar attempt (Haverkamp and Parlange, 1982), although we have encountered difficulties which are not apparent in the study of Arya and Paris (1981).

For instance, Arya and Paris calculate the saturated water content from the total porosity of the soil. Under field conditions, however, the water content at natural saturation will often be attained long before all pores are filled with water, as air entrapment occurs. Our study has also led us to believe that the particle-size distribution is useful to predict the wetting boundary of the retention curve only. Some precautions concerning hysteresis effects should be taken in the analysis at that level where pore-size distribution is linked to particle-size distribution. Those two points are obviously not crucial and could be incorporated into the model of Arya and Paris at the cost of some complications in practice.

More important is the relation between pore and particle radii (Arya and Paris, 1981; Eq. [9]) which fixes the scale of soil water pressure. This relation is not uniquely defined as it depends entirely on the subjectivity with which the number of particles in a given soil fraction (n_i) is chosen. It is not completely clear how Arya and Paris defined each fraction. As a matter of fact, if we change the size range in each fraction drastically, the fraction with an identical average particle size will have a corresponding pore size drastically different. This ambiguity of their model is reflected in their use of an equation valid for spherical pores only (Eq. [10]) without apparent ill effects in the final result, while they postulate the pores to be cylindrical. It would seem more reasonable to have the pore radius function of the particle size and soil structure only.

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Reply to "Comments on A Physicoempirical Model to Predict the Soil Moisture Characteristic from Particle-Size Distribution and Bulk Density Data"

The comment by Haverkamp and Parlange [Soil Sci. Soc. Am. J. 46:1348 (this issue)] regarding our use of total porosity of the soil in calculating saturated water content is unwarranted. We have discussed the problem of incomplete saturation and have recognized it as a source of disparity between the model predictions and experimental data. See our statement, "An incomplete saturation....maximum water content" (Arya and Paris, 1981, p. 1029). We also think that the effect of incomplete saturation can be incorporated in the Arya–Paris model. This would, however, require additional soil information. We have, as yet, not considered the problem of hysteresis in the framework of our model.

Their comment on the relation between pore and particle radii (Arya and Paris, 1981; Eq. [9]) is well taken. We thank them for pointing out the problem associated with dependence of pore radius on both the particle radius and the number of particles in the fraction. Equation [9] results from our argument for the total pore length, h_i (see Arya and Paris, 1981, Eq. [8] and the paragraph that follows). Approximating h_i from the number of particles in the fraction and the length that each particle contributes appears to us very reasonable. The problem comes in expressing the pore length of a natural soil material in terms of spherical particles. Our approach to resolve this problem leaves n_i (the number of particles in the fraction) as a factor influencing the pore radius. Alternative approaches that eliminate the effect of n_i are conceivable but may introduce other complications.

Following the comments by Haverkamp and Parlange (1982), we examined the effect on pore radius of variable n_i represented by a constant average particle radius. The results are presented in Table 1. Data presented are for a silt loam soil and apply to a portion of the particle-size distribution curve that accounts for 60% of the particles.

Table 1—Effect of variation in fraction size (with average particle size held constant) on pore radii computed by the Arya–Paris model.†

Particle-diameter interval	R_i	W_i	n_i	$n_i^{1-\alpha}$	r_i	ψ_i
μm	cm	g			cm	−cm
28–32	15.0×10^{-4}	0.050	1.33×10^{6}	4.70×10^{-3}	6.33×10^{-5}	2.32×10^{3}
25–35	15.0×10^{-4}	0.120	3.20×10^{6}	3.37×10^{-3}	5.36×10^{-5}	2.74×10^{3}
20–40	15.0×10^{-4}	0.220	5.87×10^{6}	2.68×10^{-3}	4.78×10^{-5}	3.07×10^{3}
15–45	15.0×10^{-4}	0.314	8.38×10^{6}	2.34×10^{-3}	4.46×10^{-5}	3.29×10^{3}
10–50	15.0×10^{-4}	0.397	1.06×10^{7}	2.14×10^{-3}	4.27×10^{-5}	3.44×10^{3}
5–55	15.0×10^{-4}	0.499	1.33×10^{7}	1.96×10^{-3}	4.09×10^{-5}	3.59×10^{3}
1–59	15.0×10^{-4}	0.605	1.61×10^{7}	1.82×10^{-3}	3.94×10^{-5}	3.73×10^{3}
% Change			1,110.5		37.8	60.8

† For model equations and definition of variables see Arya and Paris (1981). The soil is New Jersey Soil no. S58NJ-12-2, horizon B23t (see Soil Survey Investigations Report no. 26). $\alpha = 1.38$.

Results show that varying n_i by as much as 1,100% causes the pore radius to vary only by 38%. We, therefore, conclude that a drastic change in the size range in a fraction (with average size unchanged) will have a minor effect on the pore size.

The above example is somewhat unusual because fixing a mean particle size and varying the size range around it is not how one would use the Arya–Paris model. Normally, one would divide the particle-size distribution curve into a number of fractions starting from the end representing the smallest-size particle. In so doing both the average particle size and fraction weight would change depending on the number of fractions into which the particle-size distribution curve is divided. The effect of the number of fractions on the soil moisture characteristic is of interest. Prompted by the comments by Haverkamp and Parlange (1982) we examined this effect for a loamy sand and a silt loam soil. The results, presented in Fig. 1, show that the number of fractions from 7 to 29 did not make a significant effect on the computed soil moisture characteristics.

Haverkamp and Parlange (1982) also indicate that the manner in which we define each fraction is not clear. For their benefit and the benefit of general readership we are including an example of the computational procedure for the Arya–Paris model (see Table 2). Basically, it is a 1-g soil that is divided into a number of relatively homogeneous fractions, each fraction being represented by an average particle radius.

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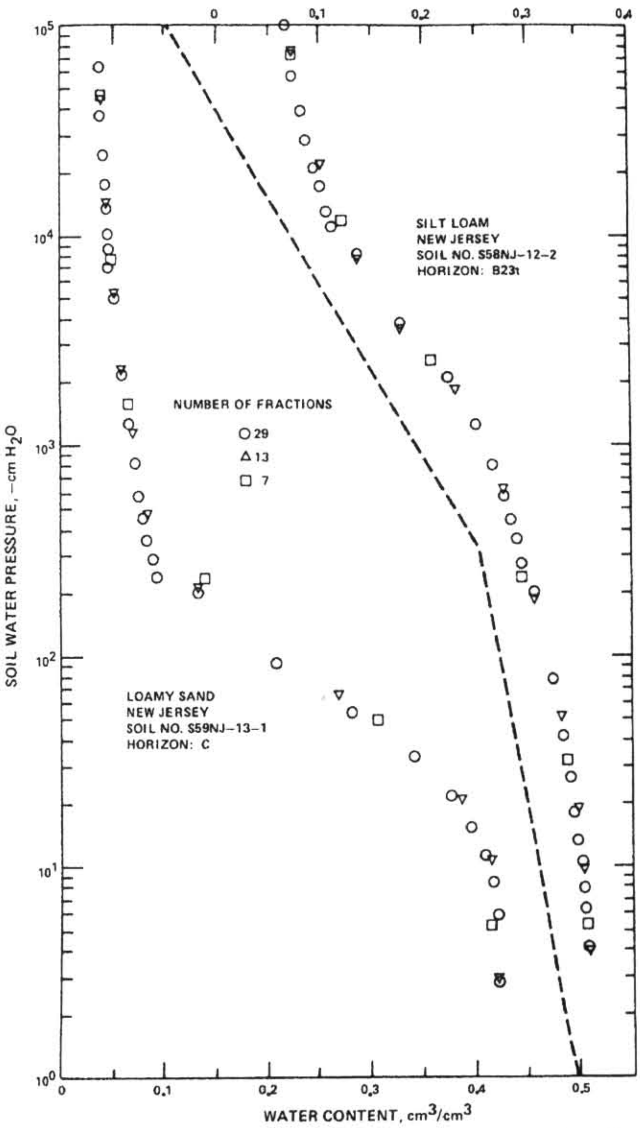

Fig. 1—Effect of the number of particle-size fractions on the soil moisture characteristic computed by the Arya–Paris model. The value of α for both soil materials is 1.38. See Eq. [1] through [10] of Arya and Paris (1981). Particle-size distribution, bulk density, and other soil data are available in SCS–USDA (1974). Soil Survey Investigations Report no. 26.

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Table 2—An example of the computational procedure for the Arya-Paris model of the soil moisture characteristic. For model equations and definition of variables, see Arya and Paris (1981). The soil is New Jersey Soil no. S58NJ-12-2, horizon B23t (see Soil Survey Investigations Report no. 26).†

Particle diameter interval	R_i	W_i	V_{v_i}	$\sum_{j=1}^{j=i} V_{v_j}$	θ_{v_i}	$\bar{\theta}_{v_i}$	n_i	$n_i^{(1-\alpha)}$	r_i	ψ_i
μm	cm	g	cm³		cm³/cm³				cm	−cm
0–1	0.25×10^{-4}	0.140	0.03001	0.03001	0.051	--	--	--	--	--
1–2	0.75×10^{-4}	0.030	0.00643	0.03644	0.062	0.057	6.41×10^{9}	1.88×10^{-4}	6.33×10^{-7}	2.32×10^{5}
2–5	1.75×10^{-4}	0.074	0.01586	0.05230	0.088	0.075	1.24×10^{9}	3.50×10^{-4}	2.01×10^{-6}	7.31×10^{4}
5–10	3.75×10^{-4}	0.076	0.01629	0.06859	0.116	0.102	1.30×10^{8}	8.25×10^{-4}	6.63×10^{-6}	2.22×10^{4}
10–20	7.5×10^{-4}	0.115	0.02465	0.09324	0.158	0.137	2.46×10^{7}	1.55×10^{-3}	1.82×10^{-5}	8.07×10^{3}
20–30	12.5×10^{-4}	0.120	0.02572	0.11896	0.201	0.180	5.54×10^{6}	2.74×10^{-3}	4.03×10^{-5}	3.65×10^{3}
30–50	20×10^{-4}	0.160	0.03430	0.15326	0.259	0.230	1.80×10^{6}	4.20×10^{-3}	7.98×10^{-5}	1.84×10^{3}
50–100	37.5×10^{-4}	0.100	0.02144	0.17470	0.295	0.277	1.71×10^{5}	1.03×10^{-2}	2.34×10^{-4}	6.28×10^{2}
100–200	75×10^{-4}	0.065	0.01393	0.18863	0.319	0.307	1.39×10^{4}	2.66×10^{-2}	7.53×10^{-4}	1.95×10^{2}
200–500	175×10^{-4}	0.070	0.01501	0.20364	0.344	0.332	1.20×10^{3}	6.76×10^{-2}	2.80×10^{-3}	5.25×10^{1}
500–700	300×10^{-4}	0.020	0.00429	0.20793	0.351	0.348	1.00×10^{2}	1.74×10^{-1}	7.70×10^{-3}	1.91×10^{1}
700–1,000	425×10^{-4}	0.015	0.00322	0.21115	0.357	0.354	1.76×10^{1}	3.36×10^{-1}	1.52×10^{-2}	9.67×10^{0}
1,000–2,000	750×10^{-4}	0.015	0.00322	0.21437	0.362	0.360	3.20×10^{0}	6.43×10^{-1}	3.70×10^{-2}	3.97×10^{0}

† $V_b = 0.5917$ cm³; $\varrho_b = 1.69$ g/cm³; $e = 0.56805$; $\gamma = 72.0$ dyn/cm; $\cos\theta = 1$; $\varrho_w = 1.0$ g/cm³; $g = 980$ cm/s²; $\alpha = 1.38$.