Modeling Structural Influences on Soil Water Retention

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ABSTRACT

A new model quantifies the effect of soil structure, considered as the arrangement of particles in the soil, on soil water retention. The model partitions the pore space into texture-related and structure-related components, the textural component being what can be deduced to exist if the arrangement of the particles were random, and the structural component being the remainder. An existing model, based on particle-size distributions, represents the textural component, and a new model, based on aggregate-size distributions, represents the structural component. This new model makes use of generalized properties that vary little from one medium to another, thereby eliminating any need for empirically fitted parameters. It postulates a particular character of the structural pore space that in some ways resembles texture-related pore space, but with pore shape related to the breadth of the aggregate-size distribution. To predict a soil water retention curve, this model requires the soil's porosity and particle- and aggregate-size distributions. Tested with measurements for 17 samples from two sources, it fits the data much better than does a model based on texture alone. Goodness of fit indicated by correlation coefficients ranged from 0.908 to 0.998 for the new model, compared with a range of 0.686 to 0.955 for the texture-based model.

STRUCTURE, considered as "the arrangement and organization of the particles in the soil" (Hillel, 1980) is a dominant influence on the hydrologic properties of an unsaturated medium. It critically affects hydraulic conductivity, water retention, and soil water diffusivity as well as essentially all solute, heat, and multiphase transport properties. Explicitly acknowledged or not, soil structure and its variability are at the heart of the issues of macropore flow and heterogeneity that are the focus of much research.

Structural influences act on various scales. Macroscopic structure, directly observable in most soils and other porous media, is obviously important. Holden (1995), for example, found ped shape to affect hydraulic properties but not in a simply discernible way. Microscopic structure can also be important, as variations in particle arrangement that are not directly apparent to the senses can influence flow properties. Nimmo and Akstin (1988) found an effect of this type in subtle variations in machine packing of a sandy soil. Although insufficient to affect bulk density, these variations caused significant differences in soil water retention and unsaturated hydraulic conductivity, K. With the same grains and equivalent porosity, different hydraulic properties could only result from a different arrangement of particles.

Soil scientists sometimes use the term *structureless* to indicate that a soil has no observable macroscopic structural features, but this designation does not rule out the possibility of microscopic structure affecting transport properties. I will avoid this term and instead

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refer to *randomly structured media*, those whose particle arrangements are completely random.

Although structural influences on hydraulic properties can be profound, direct treatments or analyses of structure have been mainly qualitative. It is important to quantify and model these effects. Of the quantitative properties of interest for this purpose, soil water retention deserves particular attention because it sometimes shows structural effects in the features of measured curves, and because it frequently serves as a basis for calculating other properties, especially K.

A desirable feature of a structure-based water retention model is a foundation in other properties, especially those that may be easier to measure, such as aggregation, organic matter, or clay content. For sounder applicability and greater insight, it is desirable for the model to be not entirely empirical but to have at least a plausible physical interpretation connecting the input data to the modeled result.

Models having these characteristics are in common use for the relation of soil texture, expressed as particle-size distributions, to soil water retention. The model of Arya and Paris (1981) is the most celebrated model that does this. Tyler and Wheatcraft (1989) showed that the Arya–Paris model has a fractal interpretation. Haverkamp and Parlange (1986) developed another model of this type, starting with physical hypotheses and combining them with empirical representations. These models often work reasonably well for media such as sands, which have a nearly random arrangement of particles, but markedly less well for media with a more organized structure.

For effects beyond those of texture, Gupta and Ewing (1992) applied the Arya–Paris model in two ways: to the particle-size distribution to model intraaggregate pores and to the aggregate-size distribution to model the interaggregate pores. As input data, their model requires the size distribution and bulk density of aggregates, as well as the particle-size distribution and the bulk and particle densities of the soil. The separate treatment of two classes of pores and the use of aggregate properties are promising ideas. The direct application of the Arya–Paris model to aggregates may not be optimal because aggregates differ from solid particles in shape and behavior. Full evaluation of this model is not yet possible because it has not been tested with measurements.

Rieu and Sposito (1991a,b) developed a model with a fractal representation of soil aggregation that predicts retention and other properties. This model requires, among other types of data, the bulk density of aggregate size classes as well as their relative abundance. For the one data set it was tested with, agreement is reasonable, but in the range drier than the test data the modeled water content drops sharply to zero in an unlikely way. This problem may result from insufficient attention to textural effects, which are likely to dominate water retention beyond the wet range.

The objectives of this study were to model soil water retention in terms of a minimal selection of other properties that are easier to measure. The starting point is a partition of the pore space into texture-related and structure-related components, the textural component being what can be deduced to exist if the arrangement of the particles were random, and the structural component being the remainder. The two components are calculated by two distinct models, an existing texture-based model and a new structure-based model. Emphasis here is on drying curves, though additional research may extend the model to wetting curves. An additional criterion for the model is for its basic assumptions and generalizations, including those that are quantitative, to be at least approximately correct in essentially all cases. This means there are no empirical parameters to be adjusted or calibrated. Finally, the model must be tested with appropriate data. This paper describes the model developed according to these criteria, presents the tests with data from two sources, and discusses the test results, the model's validity and possible improvements, and implications of the support given to the generalizations assumed in the model.

MODEL DEVELOPMENT

The first assumption is that there are only two types of influence that give retention curves their form: texture and structure. Equivalently, a retention curve is the sum of textural effects related to retention plus structural effects related to retention, giving the defining relation

$$\theta(\psi) = \theta_t(\psi) + \theta_s(\psi) \quad [1]$$

where ψ is the matric pressure, θ is the total volumetric water content, θ_t is the textural component of water content, and θ_s is the structural component. The pore space divides conceptually into a portion related to texture and the remainder, related to structure. Thus the porosity ϕ also divides conceptually into textural and structural components:

$$\phi = \phi_t + \phi_s \quad [2]$$

This partitioning is similar to that of other investigators (e.g., Bruand and Cousin, 1995), but differs in being based on a distinction between random and nonrandom arrangements, rather than pore or particle size.

To partition a curve that has been measured, it is necessary first to ascertain the texturally determined portion θ_t. A model based solely on particle-size distribution can do this if applied using ϕ_t instead of ϕ. For this purpose I have used the model of Arya and Paris (1981, 1982). This model takes the particles to be spherical and the particle-size distribution divided into discrete classes. For each particle-size class, the model assumes there is a cylindrical pore whose volume is a fraction, based on the void ratio, of the total volume of particles in that class. The length of this pore is that of a number n^α of particles, where n is the number of particles in the given size class and α is an empirical parameter. The volume and length determine the radius of this pore. Given the radius, capillarity determines the pressure at which that pore will empty, and thus, combined with the volume relation, the retention curve. Based on empirical results for several soils, Arya and Paris recommended that α equal 1.38, the value used throughout this study. Although Arya and Dierolf (1992) have developed a new version of the Arya–Paris model with a possibly superior fundamental basis, I have used the original Arya–Paris model because it produces comparable results, has wider familiarity, and permits more direct comparisons with earlier work.

For modeling $\theta_t(\psi)$, I propose to fix the texture-based poros-

ity ϕ_t at a value of 0.3. This value may not be ideal, but is probably close to optimal based on theory and observation for media that are known to be or expected to be randomly structured. For various geometrically possible regular packings of equal spheres, Deresiewicz (1958) showed that the porosity ranges from 0.260 to 0.476. A random packing would have porosity within this range but toward the low end of it because the highest porosity of these packings are metastable in a gravitational field and so would not be approximated in an actual medium. In the more general case in which there is a range of particle sizes, it is geometrically possible for the porosity to be much less than 0.260 by the mechanism of small grains fitting inside the pores of larger grains. Substantial porosity reductions are possible, though, only when the spread in sizes is appreciable (Wise, 1952). Even then, the particle-within-pore arrangement is more highly ordered, therefore less random and more improbable in a real medium. Measured porosities of media that are nearly random in structure confirm these expectations. Among the media catalogued by Mualem (1976), for example, those that are predominantly sand or glass beads have porosities or maximum water contents between 0.3 and 0.4. These media are not perfectly random, so it is reasonable for ϕ_t to be at the low end of this range.

Using data for a silt loam core sample from Shakofsky (1995), Fig. 1 shows the partitioning of the retention curve into textural and structural components. To assess the reasonableness of the results, consider the capillary relation

$$r = \frac{-R}{\psi} \qquad [3]$$

where r is the effective pore radius and R is the capillary coefficient, equal to two times the surface tension of the water divided by the cosine of the contact angle, or about 0.13 mm-kPa (Nimmo, 1992; Chen and Schnitzer, 1978; Tschapek et al., 1978). As θ_s goes to 0, the range of pore diameters related to the nonzero portion of the $\theta_s(\psi)$ curve (about −15 to 0 kPa) is about 0.01 mm and greater, mostly with diameters larger than about 0.04 mm. In the other direction, for ψ beyond about −20 kPa, θ_s stays close to zero, suggesting that texture rather than structure is important in that range. This partitioning then mainly concerns macrostructure, as microstructure would presumably involve pores <0.01 mm. For macrostructure, though, the $\theta_s(\psi)$ curve is quite reasonable,

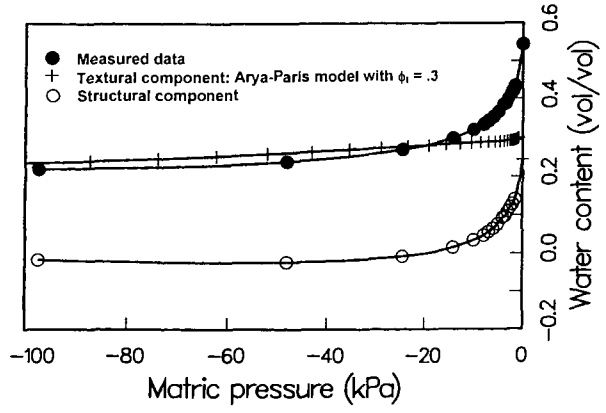

Fig. 1. The separation of a retention curve into textural and structural components. Data are for a core sample of silt loam texture (Shakofsky, 1995). The textural component is computed using the model of Arya and Paris (1981) and an assumed texture-based porosity of 0.3. The isolated structural component is the difference between the data and the textural component. The curves here illustrate the partitioning, rather than the complete model results.

showing structurally related pore sizes mostly larger than the median grain size.

The fact that θ_s becomes negative in Fig. 1 is probably insignificant, but the mechanism of pore blockage (Topp, 1971) may permit negative values — implying water content would be decreased rather than increased by an increase in structure. In a randomly structured medium there may be a large pore surrounded completely by smaller pores. This large pore cannot drain until one of its neighbors has drained. If on the other hand a structure-related pore is present that connects this otherwise blocked pore to the rest of the medium, the pore may empty earlier in the drying process. The apparent effect then is that the volume of the original large pore appears to be subtracted from the textural pore space. If that volume is greater than the new structure-related pore, there can be a net loss of water content, at some ψ, with an increase in structure. This effect may usually be negligible, as I assume in this development.

To formulate structure-based retention, the model takes information from the aggregate-size distribution, that being an easily measured property that is conceptually related to structure. For a simple formulation, it is desirable to have a convenient mathematical representation of aggregate-size distributions. Gardner (1956) suggested a lognormal distribution, characterized by geometric mean radius r_m and geometric standard deviation σ:

$$f(\log r) = \frac{1}{\sqrt{2\pi}\log \sigma} \exp\left[\frac{-(\log r - \log r_m)^2}{2(\log \sigma)^2}\right] \qquad [4]$$

where f is the relative frequency of occurrence and r is the aggregate radius.

The structure model requires relations of (i) aggregate size to pore size, and (ii) pore size to pore opening (effective capillary radius). Consider first a randomly structured medium, with a given size distribution of grains, without yet distinguishing whether those grains are aggregates or primary particles. With an assumed scaling of the relation of pore to grain sizes, the volume of a pore is a specific fraction of the volume of a grain associated with it:

$$\frac{v_{pore}}{v_{grain}} = \frac{\phi}{1 - \phi} = \eta \qquad [5]$$

where η is the void ratio. Assuming that both v_{pore} and v_{grain} go as the cube of the effective radii of the pore and grain,

$$\frac{r_{pore}}{r_{grain}} = \eta^{1/3}. \qquad [6]$$

For drying curves it is the radius not of the pore body, but of the opening, that determines the ψ at which the pore empties. Again with a scaling assumption, consider each pore, regardless of size, to have a certain ratio β of body size to opening size. Then

$$r_{opening} = r_{grain} \frac{\eta^{1/3}}{\beta} \qquad [7]$$

As with ϕ_t, β needs to have a value that is representative of randomly structured media. Again, one can consider the geometry of packed uniform spheres, for which the effective size of pore openings is about two or more times smaller than the effective size of the widest part of a pore. This suggests that β should have a value slightly >2. Considering real media, one technique is to inspect drying and wetting retention curves for media that are assumed to be randomly structured. Capillary theory suggests β should equal the ratio of the ψ values at which drying and wetting curves reach the maximum θ,

because these ψ values correspond to the inverse of the effective pore opening size (drying) and of the inverse of the effective pore body size (wetting). These ψ values are often indistinct, however, and in any case represent only the largest pores of the medium. A better approach is to use the hysteresis model of Nimmo (1992), which has a parameter essentially equivalent to β that can be optimized for the medium as a whole. This parameter can take on a wide range of values, for example about 20 or more for a silt loam core sample, but for glass bead and sand samples that approximate random macrostructure, it falls consistently between 2.1 and 2.6 (Nimmo, 1992). On the whole, theory and observation suggest a β value of about 2.2, so I use this value in the model.

To apply this relation to the structure model, several changes are necessary to account for differences between aggregates and solid grains. It is the structural porosity ϕ_s and structural void ratio

$$\eta_s = \frac{\phi_s}{1 - \phi_s} \qquad [8]$$

that are relevant, so η_s replaces η. Less straightforward is the relation between aggregates and their associated pores in terms of size and shape. Aggregates can fit more tightly together than solid grains for at least two reasons. They may be formed in place by division of the medium by cracks and holes, leaving adjacent surfaces well matched. They also are more malleable than solid grains, and especially when fairly wet, may be compressed more closely together. Because aggregates in general fit more closely together than primary particles like sand or silt, their pores are longer and narrower than would be indicated by formulas like Eq. [7], which are based on randomly structured media.

To account quantitatively for the shape of interaggregate pores, I suggest that pores may be generally narrower in media with greater orderliness, specifically with orderliness considered as uniformity of pore- or aggregate-size distribution. Figure 2 illustrates how this might be plausible in two hypothetical media. One has fairly uniform aggregates that fit together rather neatly, and the other has a diverse collection of aggregates that cannot fit together as neatly. Pores may, on the whole, tend to be wider in the more nonuniform medium. Even if all pores are equally wide, the length-to-width ratio is greater for pores associated with larger aggregates. These pores thus are relatively narrow. For the same mean aggregate size, smaller aggregates dominate, by number, in the more nonuniform medium. Therefore the more uniform medium will have a larger dominant aggregate size and relatively narrower interaggregate pores. The application of this assumption to the model requires an index of aggregate size variability, which can serve as an index of tightness of fit or narrowness of pores. Ideally this index would range from 0 for equal-sized, perfectly tight-fitting aggregates, to 1 for a maximal variation of aggregate sizes that implies a looseness of fit characteristic of randomly structured media. A parameter that has these features is the geometric standard deviation σ in the lognormal aggregate-size distribution, Eq. [4]. Direct incorporation of this index gives

$$r_{\text{opening}} = r\frac{\sigma\eta_s^{1/3}}{\beta} \qquad [9]$$

The application of capillary theory yields the matric pressure at which the pore associated with a given size of aggregate empties, and hence the aggregate size for that pressure,

$$r(\psi) = \frac{-R\beta}{\sigma\eta_s^{1/3}\psi} \qquad [10]$$

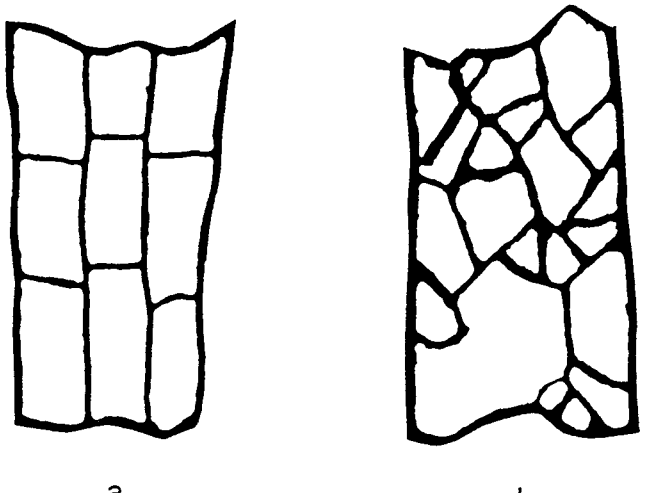

Fig. 2. Cross section of hypothetical aggregated media. Aggregates in (a) are all about the same size, and fit closely together, making the interaggregate pores long and narrow. Aggregates in (b) are more varied in size, fit together more haphazardly, and have some interaggregate pores that are relatively short and wide.

This relation and Eq. [9] involve the traditional assumption that pores are effectively circular in cross section. Interaggregate pores may generally have a more elongated cross section than interparticle pores, again for the reason that aggregates can fit together more closely. A shape-compensating factor could correct the effective radius for the difference in shape, but the model I present here retains the simple assumption of an effectively circular cross section.

To formulate $\theta_s(\psi)$ in this structure model, because of the volume relation in Eq. [5], the integral of the aggregate-size distribution in Eq. [4] gives the proportionality

$$\theta_s(\psi) \propto \int_{-\infty}^{\log r} f(\log r)\, \mathrm{d}\log r \qquad [11]$$

Since the lognormal distribution integrates to 1 over the whole domain and θ_s has the value ϕ_s for this domain, ϕ_s is the proportionality constant. Taking $f(\log r)$ from Eq. [4],

$$\theta_s(\psi) = \frac{\phi_s}{\sqrt{2\pi}\log\sigma}\int_{-\infty}^{\log r}\exp\left[\frac{-(\log r - \log r_m)^2}{2(\log\sigma)^2}\right]\mathrm{d}\log r \qquad [12]$$

Changing variables to

$$u = \frac{\log[r(\psi)] - \log r_m}{\log\sigma} \qquad [13]$$

gives

$$\theta_s(\psi) = \frac{\phi_s}{\sqrt{2\pi}}\int_{-\infty}^{u}\exp\left[\frac{-u^2}{2}\right]\mathrm{d}u \qquad [14]$$

For convenience in calculation, the cumulative normal-distribution (Gaussian) function

$$F_n(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x}\exp\left[\frac{-u^2}{2}\right]\mathrm{d}u \qquad [15]$$

allows the structural retention Eq. [14] to be rewritten

$$\theta_s(\psi) = \phi_s F_n\left\{\frac{\log[r(\psi)] - \log r_m}{\log\sigma}\right\} \qquad [16]$$

Having the form of a cumulative lognormal distribution, Eq.

Table 1. Parameters used in computing the structure model results, including the porosity and the parameters of the lognormal aggregate-size distribution.

Sample identification	Porosity	Geometric mean diameter	Geometric standard deviation
IU030	0.4520	0.88	0.18
IU080	0.4705	1.0	0.16
IU145	0.4500	2.5	0.18
IU225	0.5067	1.2	0.23
ID030	0.4584	0.74	0.23
ID080	0.5145	0.84	0.20
ID145	0.5320	1.2	0.18
ID225	0.5504	2.05	0.19
Ariana	0.4602	0.83	0.348

[16] provides a physically reasonable shape for a retention curve. Adding θ_s to the Arya–Paris-based θ_t gives a combined texture–structure model suitable for direct comparison with measurements.

For comparison, θ_s can be computed using the Arya–Paris model applied to the aggregate-size distribution with porosity ϕ_s. Adding this θ_s to the Arya–Paris-based θ_t, gives an Arya–Paris dual-porosity (APDP) model. This is very similar to the Gupta–Ewing (1992) model but it uses the assumed ϕ_t value to partition the pore space and therefore does not require aggregate density data. It may produce essentially the same results, but with the advantage that more data sets are presently available for testing it.

MODEL TEST

A test of this new texture–structure model requires data sets that include the aggregate-size and pore-size distributions in addition to the retention curve. Even though these are routine measurements, they are seldom done in combination. The data of Shakofsky (1993, 1995), for undisturbed and disturbed (simulated waste trench) soil at the Idaho National Engineering Laboratory (INEL), include the required information. This study uses data for 16 samples, two at each of four depths in both the undisturbed and disturbed locations. The text here identifies them with notation such as IU145b, where the first letter denotes the site (INEL), the second whether undisturbed or disturbed (U or D), and the number the depth in centimeters. The letter *a* or *b* distinguishes between the two samples from each location and depth. Water retention was measured with minimally disturbed core samples in the laboratory using the submersible pressure outflow cell method (Constantz and Herkelrath, 1984). All measurements were done on core samples without further disturbance or repacking. Note that *disturbed* means that the field location had been disturbed once, 6 yr before sampling. Another adequate data set is for Ariana soil, a silty clay loam, measured by Bousnina in 1984 and quoted by Rieu and Sposito (1991b). Bousnina measured water retention in the field using a method of Vachaud et al. (1981).

Fits of the lognormal distribution to aggregate-size measurements yield values of geometric mean and standard deviation (Table 1). The aggregate-size distribution measurements of Shakofsky (1995) were interpolated linearly over depth to correspond to the depths of the water retention measurements. The aggregate-size distributions were measured for soil near the holes used for both sets of samples *a* and *b*. Four size classes characterize the aggregates at each depth sampled, but this is adequate to represent the lognormal distribution. Inserting the values from Table 1 into Eq. [16] and [10] gives θ_s. Application of the Arya–Paris model to the particle-size distribution and ϕ_t gives θ_t for combining with θ_s to produce modeled results comparable to measurements.

Figure 3 and Tables 2 and 3 give test results for the new model and two others. Comparison to fits of the standard Arya–Paris model, computed using ϕ in the normal fashion, indicate the effect of considering texture only. Comparison to fits of the APDP model can show whether assumptions described above are more appropriate than those of Arya–Paris when applied to aggregates. Table 2 gives correlation coefficients between the calculated and measured retention curves for all 17 data sets. The correlation coefficients were computed with the measured values of θ compared with model calculations interpolated to the same value of ψ. Table 3 gives the residual sum of squares for all tests, included in addition to the correlation coefficients because it gives an indication of fit quality closer to what would be judged by eye. Figure 3 shows six sets of the fitted curves, including, on the left side, the best fits by the new model (IU80a), the APDP model (IU80b), and the Arya–Paris model (IU225b). The right side at the top again has IU80a data, but an expanded view of the wettest portion only. The other graphs on the right side show two different media, one an INEL sample from shallow depth in the disturbed soil (ID30a), the other the Ariana soil.

DISCUSSION

Agreement between the data and the combined texture–structure model is mostly good and sometimes outstanding, as for example in the fit of IU80a (Fig. 3, top left and right). Figure 3 as a whole understates the superiority of the fits of the new model because (i) the 100 kPa ψ span in five of the six graphs compresses the structurally important 0 to 10 kPa region into a small area of each plot, and (ii) the five data sets include both of the cases where the new model is inferior, but only two of the 10 sets where it is clearly superior.

With a single exception (IU225a, Fig. 3, lower left), the Arya–Paris fits are much worse than those of the new model. The Arya–Paris model, having no explicit structural component, does not have the distinct drop of θ near zero ψ that is typical of structured media.

The APDP model fits slightly better than the new model in one case (IU80b, Fig. 3, left middle) and about equally well in six cases. It is clearly inferior to the new model in 10 cases. The defect of most APDP fits is that their θ values drop much too sharply near zero ψ. The structural component of the new model, apart from the better fits it provides in most cases, has a fundamental advantage over APDP in having no parameters that are purely empirical, whereas the APDP model has the α

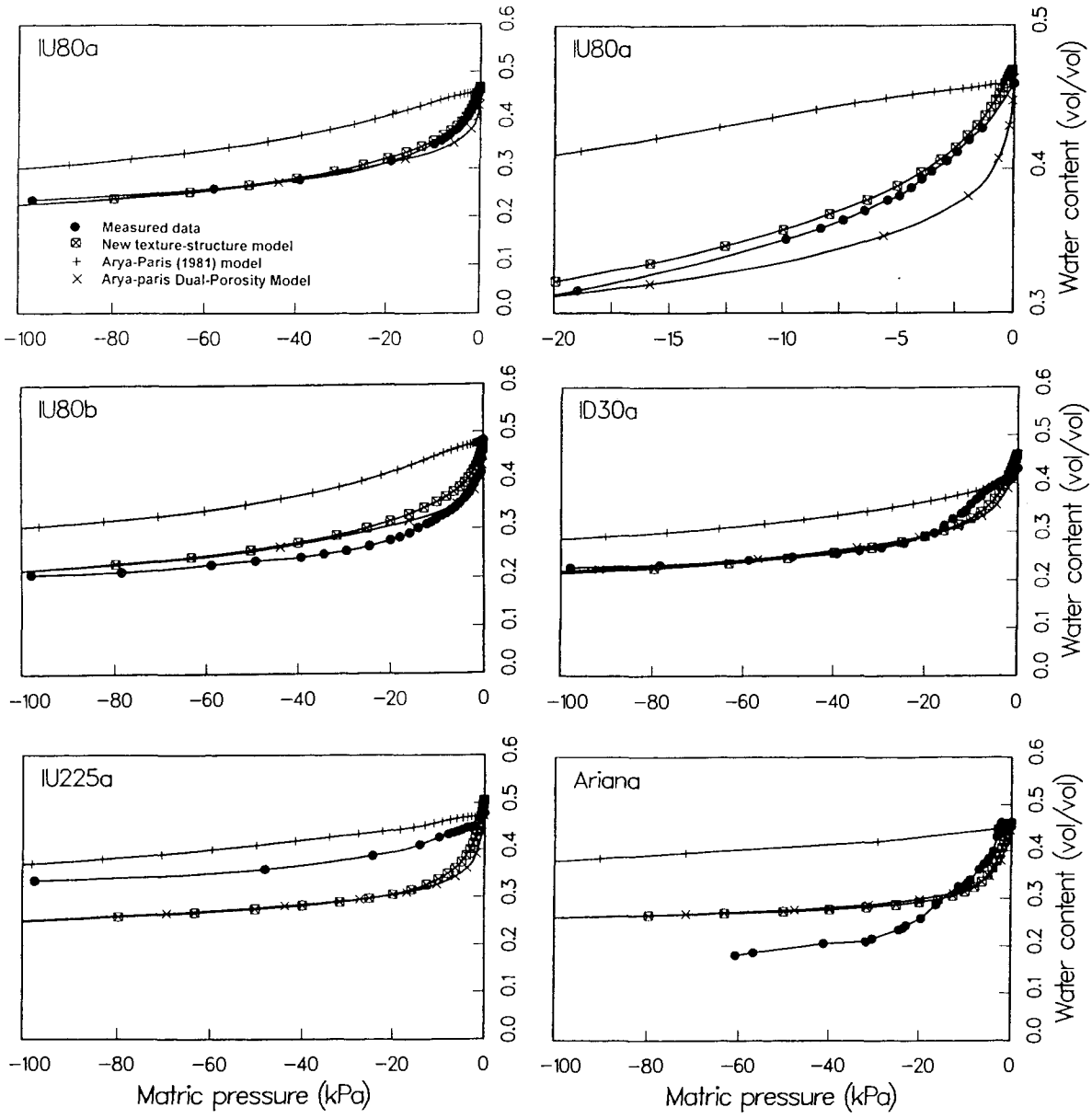

Fig. 3. The fit of the combined texture–structure model, with two other models for comparison, to data from selected INEL core samples and from the Ariana soil. The three graphs on the left show, from top to bottom, the best fitted results of the new model, the Arya–Paris dual-porosity model, and the original Arya–Paris model. The graph at top right gives an expanded view of the wetter, more structurally important portion of the results shown at top left. The other graphs show fits to data selected for variety of soil, location, and depth.

parameter whose value is obtained only from experience with other soils.

There is no obvious correlation of fit quality with depth of sampling, degree of soil disturbance, or source of data. It may seem at first puzzling that there is no systematic difference between the undisturbed and disturbed INEL results, given the expected effect of disturbance on structure. The lack of such a difference, though, is consistent with the observation that the measured retention data themselves did not show pronounced structural differences. One contributing factor in this is that all of the measurements were done on core samples. Another is that the disturbed area had had 6 yr of exposure to natural structure-modifying influences before sampling.

The observed agreement with measurements lends support to the new model's underlying bases: (i) the conceptual partitioning of pore space, (ii) pore-size calculations based on particle- and aggregate-size distributions, (iii) the use of generalized properties rather than empirically fit parameters, and (iv) a specific postulated character of interaggregate pores. Each of these is worth considering to note the relation to physical reality as well as possible improvements and extensions.

The division of the retention curve, and of pore space, into textural and structural components is to some degree clearly an oversimplification. Influences such as the wettability of the soil can also be significant. The model results here, though, suggest that texture and structure can be influential to the point where they

Table 2. Goodness of fit, computed as correlation coefficients, for the new texture–structure model and two other models for comparison. Italics indicate the best fit by this measure for each sample.

Sample identification	Arya–Paris model	Arya–Paris dual-porosity model	New texture–structure model
IU30a	0.942	0.970	*0.978*
IU30b	0.751	0.971	*0.981*
IU80a	0.904	0.989	*0.997*
IU80b	0.862	0.982	*0.990*
IU145a	0.894	*0.951*	0.937
IU145b	0.863	*0.976*	0.968
IU225a	0.857	*0.961*	0.958
IU225b	*0.955*	0.939	0.908
ID30a	0.932	0.927	*0.936*
ID30b	0.909	0.893	*0.917*
ID80a	0.835	0.979	*0.993*
ID80b	0.840	0.981	*0.992*
ID145a	0.725	0.982	*0.987*
ID145b	0.686	0.981	*0.989*
ID225a	0.765	0.984	*0.991*
ID225b	0.748	0.996	*0.998*
Ariana	0.904	*0.984*	0.953

dominate all retention-related phenomena. This division of pore space has the additional advantage of framing the concept of soil structure in a way that lends itself to quantification.

The representation of the textural component with a model based on particle-size distribution is supported by the applicability of texture-based models to media that have nearly random structure. While the examples here used the existing Arya–Paris model, alternatives are certainly possible, and may be preferable.

The representation of the structural component with a model based on aggregate-size distribution is supported mainly by the test results. One issue of plausibility is the use of aggregate size to indicate pore size, which appears reasonable by analogy to the case of particles. Another is the embodiment of structural information solely in the aggregate-size distribution. It is helpful to consider that the properties of aggregates may to some extent serve as a surrogate for other structure-related factors. The pores related to macroscopic structure, whether closely linked to aggregation (e.g., shrinkage cracks), or less directly linked (e.g., wormholes), tend to be rather long and narrow, so that a common treatment may be appropriate. Aggregate size is likely to correlate positively with other possible indicators of structure, such as worm and root activity, and clay and organic matter content, as well as with the nature of the structural pore space in the way this model postulates. Thus the explicit dependence on aggregate size alone does not mean the model will be inapplicable where the main elements of structure seem more closely related to other factors.

Table 3. Residual sum of squares for the new texture–structure model and two other models. Italics indicate the best fit by this measure for each sample.

Sample identification	Arya–Paris model	Arya–Paris dual-porosity model	New texture–structure model
IU30a	0.00168	0.00133	*0.00060*
IU30b	0.00719	0.00087	*0.00015*
IU80a	0.00488	0.00054	*0.00004*
IU80b	0.01288	*0.00038*	0.00108
IU145a	0.00312	0.00378	*0.00180*
IU145b	0.00638	0.00183	*0.00050*
IU225a	0.00894	0.00453	*0.00246*
IU225b	*0.00107*	0.00756	0.00532
ID30a	0.00226	0.00060	*0.00035*
ID30b	0.00519	0.00288	*0.00161*
ID80a	0.01070	*0.00020*	0.00030
ID80b	0.01990	*0.00062*	0.00071
ID145a	0.01092	0.00033	*0.00009*
ID145b	0.01749	0.00365	*0.00151*
ID225a	0.02657	0.00027	*0.00016*
ID225b	0.04075	0.00132	*0.00101*
Ariana	0.01954	0.00329	*0.00257*

The model relies on generalized properties, with parameter values not optimized but based on typical properties of randomly structured media. The textural porosity of 0.3 gives a structural porosity ranging from 0 to about 0.2 for typical soils. The ratio of pore body size to pore opening size is taken to always equal 2.2. Of course these parameters could be varied to optimally fit retention data, but reliance on the fixed values minimizes data requirements and increases the model's versatility and ease of use. The model requires no retention measurements, and unlike comparable models using aggregate-size data (Rieu and Sposito, 1991a,b; Gupta and Ewing, 1992), it requires no aggregate-density data. The avoidance of optimization is possible in part because the intended accuracy of the model is modest, but also because the parameters required do not vary much for the case of randomly structured media, the only case for which the theoretical basis of the model requires them to apply. It may be possible to improve the model with fine tuning of the recommended ϕ_t and β values as more data are compiled. If such refined values are desirable, they can perhaps be assigned on the basis of general soil classifications.

The model has been developed for drying curves. An interpretation of hysteresis as resulting from Haines jumps (Haines, 1930) would suggest that a wetting curve might be generated by letting β equal 1 instead of 2.2, but this has not been tested. A separate hysteresis model such as that of Nimmo (1992) can provide wetting curves, normally with a requirement of additional information.

The model's representation of structure-related pores differs in several respects from that of texture-related pores. This different representation is supported by the fact that it has generally better fits and a less empirical formulation than the APDP model. One critical element of the structural representation relates pore shape to the uniformity of pore size: the narrowness of interaggregate pores, associated with the orderliness of the medium, correlates with the uniformity of the aggregate-size distribution. The model quantifies this using the geometric standard deviation of aggregate size as an index. Another element is that the openings of structure-related pores are small by the measure of their associated aggregate sizes (Eq. [9]), compared with openings of texture-related pores by the measure of their associated particle sizes (Eq. [7]). These relationships are to be expected because aggregates can fit more closely together than primary particles. Moreover, the computed structural pore sizes are consistent with the sizes

deduced for examples such as that in Fig. 1. Many of these points are reflected in the APDP model's overly precipitous decline of θ near zero ψ, suggesting that structural pores are indeed longer and narrower than textural pores.

CONCLUSIONS

The water-retention model presented here quantifies the effects of structure in a useful way. It gives great improvement over a model based on texture alone, and modest improvement over a model that quantifies structure with a formulation developed for the quantification of textural effects. In tests with 17 data sets, this new model gives good fits without a need to optimize parameters individually for each data set. The measured data required are the porosity, particle-size distribution, and aggregate-size distribution. The quality of the fits provides evidence supporting a partition of pore space into textural and structural components, the use of generalized properties, and the basing of retention properties on a particular relation of aggregate size to pore size that postulates relatively narrow structural pores.

Superiority of fit compared with models such as Arya–Paris comes in large part from the contribution of information supplemental to texture and porosity, namely the aggregate-size distribution. The magnitude and systematic nature of the improvement suggest that this model makes effective and reasonable use of the additional data.

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REFERENCES

Arya, L.M., and T.S. Dierolf. 1992. Predicting soil moisture characteristics from particle-size distributions: An improved method to calculate pore radii from particle radii. p. 115–124. *In* M.Th. van Genuchten et al. (ed.) Indirect methods for estimating the hydraulic properties of unsaturated soils. Proc. Worksh., Riverside, CA. 11–13 Oct. 1989. Univ. of Calif., Riverside.

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.

Arya, L.M., and J.F. Paris. 1982. Reply to "Comments on 'A physico-empirical model to predict the soil moisture characteristic from particle size distribution and bulk density data.'" Soil Sci. Soc. Am. J. 46:1348–1349.

Bruand, A., and I. Cousin. 1995. Variation of textural porosity of a clay-loam soil during compaction. Eur. J. Soil Sci. 46:377–385.

Chen, Y., and M. Schnitzer. 1978. The surface tension of aqueous solutions of soil humic substances. Soil Sci. 125:7–15.

Constantz, J., and W.N. Herkelrath. 1984. Submersible pressure outflow cell for measurement of soil-water retention and diffusivity from 5 to 95°C. Soil Sci. Soc. Am. J. 48:7–10.

Deresiewicz, H. 1958. Mechanics of granular matter. Adv. Appl. Mech. 5:233–306.

Gardner, W.R. 1956. Representation of soil aggregate-size distribution by a logarithmic-normal distribution. Soil Sci. Soc. Am. Proc. 20:151–153.

Gupta, S.C., and R.P. Ewing. 1992. Modeling water retention characteristics and surface roughness of tilled soils. p. 379–388. *In* M.Th. van Genuchten et al. (ed.) Indirect methods for estimating the hydraulic properties of unsaturated soils. Proc. Workshop. U.S. Salinity Lab. and Dep. Soil and Envir. Sci., U. Calif., Riverside.

Haverkamp, R., and J.-Y. Parlange. 1986. Predicting the water-retention curve from particle-size distribution: 1. Sandy soils without organic matter. Soil Sci. 142:325–339.

Haines, W.B. 1930. Studies in the physical properties of soil. V. The hysteresis effect in capillary properties and the modes of water distribution associated therewith. J. Agric. Sci. (Cambridge) 20: 97–116.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, New York.

Holden, N.M. 1995. Temporal variation in ped shape in an old pasture soil. Catena 24:1–11.

Mualem, Y. 1976. A catalogue of the hydraulic properties of soils. Proj. 442. Technion, Israel Inst. of Technology, Haifa.

Nimmo, J.R. 1992. Semiempirical model of soil water hysteresis. Soil Sci. Soc. Am. J. 56:1723–1730; 57:936.

Nimmo, J.R., and K.C. Akstin. 1988. Hydraulic conductivity of a sandy soil at low water content after compaction by various methods. Soil Sci. Soc. Am. J. 52:303–310.

Rieu, M., and G. Sposito. 1991a. Fractal fragmentation, soil porosity, and soil water properties: I. Theory. Soil Sci. Soc. Am. J. 55: 1231–1238.

Rieu, M., and G. Sposito. 1991b. Fractal fragmentation, soil porosity, and soil water properties: II. Applications. Soil Sci. Soc. Am. J. 55:1239–1244.

Shakofsky, S.M. 1995. Changes in soil hydraulic properties caused by construction of a simulated waste trench at the Idaho National Engineering Laboratory, Idaho. U.S. Geol. Surv. Water-Resour. Invest. Rep. 95–4058.

Shakofsky, S.M. 1993. Changes in the hydraulic properties of a soil caused by construction of a waste trench at a radioactive waste disposal site. M.S. thesis. San Jose State Univ., San Jose, CA.

Tschapek, M, C.O. Scoppa, and C. Wasowski. 1978. The surface tension of soil water J. Soil Sci. 29:17–21.

Topp, G.C. 1971. Soil-water hysteresis: The domain model theory extended to pore interaction conditions. Soil Sci. Soc. Am. Proc. 35:219–225.

Tyler, S.W., and S.W. Wheatcraft. 1989. Application of fractal mathematics to soil retention estimation. Soil Sci. Soc. Am. J. 53:987–996.

Vachaud, G., M. Vauclin, and J. Colombani. 1981. Bilan hydrique dans le Sud Tunisien: I. Caracterisation experimentale des transferts dans la zone non-saturee. J. Hydrol. (Amsterdam) 49:31–52.

Wise, M.E. 1952. Dense random packing of unequal spheres. Philips Res. Rep. 7:321–343.