Soil Phys. Cond. Plant Growth, Jpn.
土壌の物理性
No. 74, p. 17～27 (1996)

Evaluation of Two Soil Water Retention Models for the Prediction of Hydraulic Conductivity of Daisen Kuroboku (Volcanic Ash) Soil

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Abstract

It is known that soils of volcanic origin are generally well-aggregated. To describe their retention characteristics with the unimodal model of van Genuchten (1980), and subsequently predicting the hydraulic conductivity from it can lead to some errors. In this paper both the multi-porosity water retention model of Durner (1992) and the van Genuchten model are used to describe the retention characteristics of some samples of Daisen Kuroboku soil (Andosol). The two types of retention models are then combined separately with the conductivity model of Mualem (1976) to estimate the hydraulic conductivity of the samples. Estimated hydraulic conductivity using the two retention models differed by orders of magnitude. The disagreement between the estimated conductivities may be due to inadequate description of the retention data by the van Genuchten model.

Key words : Soil water retention, Hydraulic conductivity, Unimodal retention model, Multimodal retention model, Kuroboku soil.

I. Introduction

Volcanic ash soils are found extensively in all parts of Japan and cover an area of about 60,641 km^2, i.e., about 16.4% of the total land area (Adachi, 1971). The soils have generally a well-developed soil structure and abounds in many loose voids. For instance, Tabuchi *et al.* (1963) established that for a Kanto loam (Andosol) percolation through such voids is about one-sixth of total porosity. They postulated that the loose voids constitute comparatively a uniform channel in which permeability was in the order of 10^{-2} cms^{-1}. Contrasting with the above is the water channel in the lower layers of soil which contain little organic matter and have tubal passages composed of a complicated massive structure, with permeability in the order of 10^{-3} cms^{-1}. According to Takenaka (1973), even if volcanic ash soil is compacted, its permeability does not deteriorate but remains high, in the order of 10^{-3} cms^{-1}. However, in the lower soil layer with small amounts of organic matter, compaction lowers the permeability to the range of 10^{-5}–10^{-6} cms^{-1}. In recent years some researchers (e.g., Tokunaga, *et al.*, 1984, 1986 ; Soma, *et al.*, 1983 ; Mori, *et al.*, 1992) have used soft X-ray and stereoscopic techniques to confirm the existence of large pores (macro-pores) in especially the topsoil of volcanic ash soils.

Of all soil hydraulic properties, the unsaturated hydraulic conductivity K is the most difficult to measure. Prediction methods are frequently used where the shape of the conductivity function is estimated from the more easily measured water retention characteristic. Errors in the conductivity can arise either from an invalidity of the prediction model for a given soil, or from an incorrect description of the retention data. According to Durner (1994) the second error source is particularly important for soils with heterogeneous pore systems that cannot be adequately described by the usually used retention functions. To describe the retention characteristics of such soils, they proposed a flexible soil moisture retention function $\theta(h)$, by superimposing unimodal retention curves of the van Genuchten (1980) type (Fig. 1). This retention model was then combined with the Mualem (1976) conductivity prediction model to estimate the conductivity of soils with heterogeneous pore systems.

Durner (1994) stated that undisturbed soils frequently have pore systems that are different from the unimodal, approximately normal distributed type (see Fig. 1). Consequently, attempts to fit their retention data with a simple sigmoidal curve lead to unsatisfying results. The deviations that occur from using the unimodal model are assumed to be within the confidence interval of the corresponding measured values. However, if such deviations are not within the confidence interval, they would then be relevant and cannot be ignored. Based on this, Durner (1994) defined the term 'heterogeneous' with respect to hydrological properties. They designated a pore system as heterogeneous if the pore-size distribution of a representative elementary area (Bear and Bachmat, 1991) cannot be correctly described by the van Genuchten function (or any other unimodal retention functions mentioned in the literature). Pore systems that are non-conform with a simple sigmoidal retention characteristics may be a result of specific particle-size distributions or be due to the formation of secondary pore systems by various soil genetic processes.

Daisen Kuroboku soil being of volcanic origin and therefore well-structured, can be expected to portray significant secondary pore properties. To be able to do any meaningful water balance simulation studies on such soils, it is important to predict its hydraulic properties as accurately as possible. The objective of this paper is to compare the results obtained by the van Genuchten-Mualem method with the recent approach of Durner-Mualem in predicting the hydraulic conductivity of Daisen Kuroboku soil. The differences and limitations of the two approaches are discussed.

II. Model Approaches

Water Retention Model

Several functions have been proposed to empirically describe the soil water retention curve (Brooks and Corey, 1964 ; Su and Brooks, 1975 ; Haverkamp *et al.*, 1977 ; van Genuchten,

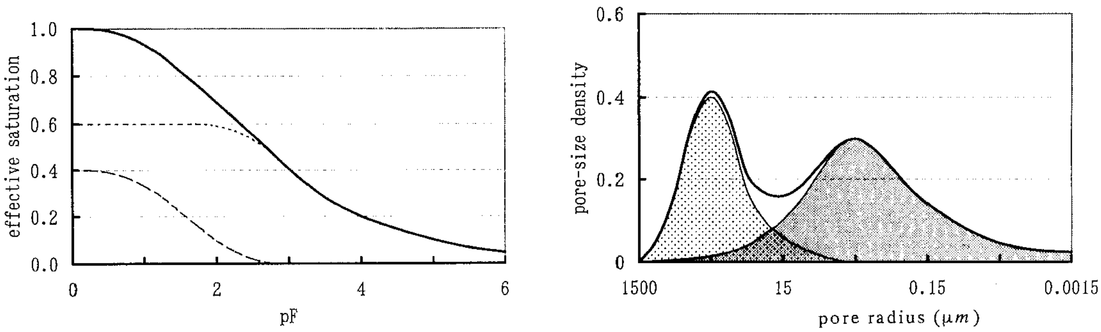

Fig. 1 Construction of a multimodal retention function, [3]. Top : Bimodal retention curve (solid line), unimodal subcurve for textural poresystem (short dashed line, $w_1=0.6$, $\alpha_1=0.005\,\mathrm{cm}^{-1}$, $n_1=1.4$, $m_1=1-1/n_1$) ; and unimodal subcurve for a secondary pore system (long dashed line, $w_2=0.4$, $\alpha_2=0.1\,\mathrm{cm}^{-1}$, $n_2=2.2$, $m_2=1-1/n_2$). Bottom : Pore size distributions of bimodal function (solid line), of textural pore system (dark shaded), and of secondary system (light shaded).

1980). The most popular among these functions are the equations of Brooks and Corey (1964), written in a dimensionless form as :

$$S_e=\begin{cases}(ah)^{-\lambda} & (ah>1)\\ 1 & (ah\leq 1)\end{cases} \qquad (1)$$

and, more recently the equation of van Genuchten (1980) :

$$S_e=\left[1+(ah)^n\right]^{-m} \qquad (2)$$

where S_e is effective saturation (dimensionless), defined by $S_e=(\theta-\theta_r)/(\theta_S-\theta_r)$, with ($\theta_s$ and θ_r indicating the saturated and residual volumetric water contents, respectively ; h is the soil water pressure head (centimeters) ; $\alpha>0$ (centimeters) is a scaling factor that determines the position of the pore size maximum ; and λ, n, and m are dimensionless curve parameters, subject to $\lambda>0$, $m>0$, and $n>1$.

The above retention functions reflect unimodal, and if continuously differentiable, smooth normal to log-normal shaped pore-size distributions (Durner, 1994). The similarities between the Brooks and Corey and the van Genuchten functions have been discussed at length by Durner (1994) ; and the conclusion that was drawn is that the van Genuchten retention model in its general form (2) represents a continuous, smooth, unimodal, and bell-shaped pore-size distribution with the parameter α primarily determining the position of the pore density maximum and the parameters m and n determining the width toward the fine and large pore sizes. To obtain the conductivity estimates as closed-form functions, the parameters of the van Genuchten equation are subjected to the additional constraint $m+1/n=1$ in combination with the conductivity prediction model of Mualem (1976). According to Durner (1994), this constraint eliminates some of the flexibility of the van Genuchten function, since pore-size distributions that extend far toward fine pores are then always coupled with relatively broad distributions toward large pores, and vice versa. Even though this is fairly good in accordance with experimental data for many soils, there are some fine-textured soils (e.g., Daisen Kuroboku), however, where the constraint attributes part of the pore space to unrealistically large pores.

Consequently, attempts to fit the retention data of fine-textured soils with simple sigmoidal curves lead to unsatisfactory results. Durner (1994) reviewed some typical fitting errors likely to occur and proposed a multimodal retention function for proper description of fine-textured soils (i.e., soils with heterogeneous pore systems). It was constructed by a linear superposition of subcurves of the van Genuchten type (Durner, 1992) (see Fig. 1) :

$$S_e=\sum_{i=1}^{k} w_i\left[\frac{1}{1+(\alpha_i\cdot h)^{n_i}}\right]^{m_i} \qquad (3)$$

where k is the number of "subsystems" that form the total pore-size distribution, and w_i are weighting factors for the subcurves, subject to $0<w_i<1$ and $\Sigma w_i=1$. As for the unimodal curve, the parameters of the subcurves (α_i, n_i, m_i) are subject to the conditions $\alpha_i>0$, $n_i>1$ and $m_i>1$.

The multimodal retention model, (3), keeps the functional properties of the basic van Genuchten model, but is able to account for deviations arising as a result of secondary pores due to the increased number of coefficients. It is continuously differentiable, assymptotic to a zero slope towards the fine and large pores, and strongly monotonic over the whole moisture range. By keeping k small, the function is well-behaved for interpolation purposes, reducing the noise in measured data while following the shape of the measured curve (Durner, 1994). The coefficients of (3) can, to a certain degree, be interpreted in the same manner as the basic van Genuchten coefficients, namely, $h_i=1/\alpha_i$, indicating the positions of pore density maxima, and $n_i m_i$ and n_i/m_i, determining the width of the underlying pore-size distributions. However, if the pore system is not distinctly bimodal or multimodal, the coefficients of the multimodal retention function tend to be highly correlated. For this reason, Durner

(1994) suggests that the parameters must be seen as curve shape coefficients like those of any alternative function rather than as having physical meaning.

Conductivity Estimation

The relative hydraulic conductivity function is computed by numerical evaluation of Mualem's (1976) predictive model based on the unimodal or multimodal representation of $h(S_e)$:

$$K = S_e^{\tau}\left[\frac{f(S_e)}{f(1)}\right]^2 \tag{4}$$

where f is given by

$$f(S_e) = \int_0^{S_e} \frac{1}{h(S'_e)} dS'_e \tag{5}$$

In (4), S_e^{τ} is an empirical correction function, which allows for a priori unknown effects of pore connectivity and tortuosity in Mualem's model. Mualem (1976) found an average value of $\tau = 0.5$ to be optimal for a set of 45 soil samples. The absolute conductivity $K_{abs}(S_e)$ can be calculated by matching the predicted function $K(S_e)$ to a matching value K_{ref}, measured at some reference saturation S_{ref}, according to

$$K_{ads}(S_e) = K_{ref} \cdot K(S_e)/K(S_{ref}) \tag{6}$$

III. Materials and Methods

The soil samples used in this study were obtained from the Chugoku region of western Japan. Samples **A** and **F** were from apple orchards, samples **B** and **C** from Japanese pear

Table 1 Parameters of samples A, B, and C at various depths of soil

Classification	Sample A 5 cm	15 cm	25 cm	35 cm	Sample B 5 cm	15 cm	25 cm	35 cm	Sample C 5 cm	15 cm	25 cm	35 cm
Density, g cm^{-3}	0.61	0.74	0.85	0.84	0.46	0.63	0.61	0.60	0.65	0.63	0.70	0.57
					Unimodal van Genuchten							
θ_s, cm^3 cm^{-3}	0.502	0.598	0.574	0.602	0.607	0.644	0.653	0.655	0.670	0.662	0.632	0.646
θ_r, cm^3 cm^{-3}	0.156	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.140
α, cm^{-1}	0.0653	0.1444	0.0786	0.0140	0.4774	0.0237	0.0428	0.0485	0.0217	0.0626	0.0398	0.0410
n	1.238	1.117	1.092	1.091	1.095	1.110	1.109	1.117	1.113	1.117	1.129	1.216
m	0.193	0.104	0.084	0.083	0.086	0.099	0.098	0.105	0.102	0.105	0.114	0.177
					Multimodal van Genuchten *-Bimodal for all soil samples at all depths except sample A at the 35 cm depth							
θ_s, cm^3 cm^{-3}	0.502	0.598	0.574	0.602	0.607	0.644	0.653	0.655	0.670	0.662	0.632	0.646
θ_r, cm^3 cm^{-3}	0.170	0.181	0.192	0.275	0.142	0.187	0.205	0.160	0.189	0.148	0.154	0.175
w_1	0.54	0.47	0.42	0.29	0.46	0.31	0.35	0.37	0.32	0.40	0.38	0.55
α_1, cm^{-1}	0.0322	0.0568	0.0489	0.0803	0.1281	0.0793	0.0518	0.0569	0.0809	0.0392	0.0297	0.0262
n_1	2.575	2.102	1.78	1.448	2.051	1.546	1.984	1.758	1.479	2.038	2.214	1.898
m_1	0.612	0.524	0.438	0.309	0.512	0.353	0.496	0.431	0.324	0.509	0.548	0.473
w_2	0.46	0.53	0.58	0.34	0.54	0.69	0.65	0.63	0.68	0.60	0.62	0.45
α_2, cm^{-1}	0.0005	0.0006	0.0005	0.0008	0.0004	0.0003	0.0004	0.0004	0.0003	0.0003	0.0005	0.0004
n_2	1.642	1.433	1.438	1.868	1.586	1.629	1.707	1.55	1.62	1.576	1.536	1.596
m_2	0.391	0.302	0.305	0.465	0.37	0.386	0.414	0.355	0.383	0.366	0.349	0.373
w_3				0.37								
α_3, cm^{-1}				0.00009								
n_3				2.655								
m_3				0.623								

*-At the 35 cm depth the trimodal fit was the best with θ_s and θ_r fixed. θ_r was fixed by multiplying the measured value at pF 4.2 by 0.8 as suggested by Durner (1994).

orchards, sample **D** from a lawn while sample **E** was taken from a vegetable (carrot) farm. The first five soil samples are of volcanic ash origin and are broadly described as the "Kuroboku" soils in the Japanese soil classification system (or Andosol). The soils have a characteristic black color throughout the profile and contain various levels of organic matter. They are generally light compared to mineral soils and their bulk density values at different soil depths are given in tables 1 and 2. The sixth sample is, however, not a Kuroboku soil ; it is of mineral origin which was exposed to the surface during land reclamation process. It is also characterized by low bulk density values as observed in table 2. All the samples are characterized by high saturation water contents, θ_s and do not fit into the typical values of soil textural groups given by Rawls *et al.* (1982) or Carsel and Parrish (1988).

Undisturbed core samples were collected from the field at the depths indicated in the tables 1 and 2 using 100 cm^3 stainless steel cores for retention characteristics determination in the laboratory. All the samples taken were in the vertical direction only. After pre-saturation for 24-hours and recording the weight, the hanging column method (JSSMFE, 1983) was used to determine the retention characteristics between saturation and pF 2.2, and the centrifuge method (JSSMFE, 1983) was used for pF from 2.5 to 4.2. Durner (1994) notes that lack of data between saturation and pF 2.0 can lead to unreliable conductivity estimates regardless of

Table 2 Parameters of samples D, E, and F at various depths of soil

Classification	Sample D				Sample E				Sample F		
	5 cm	15 cm	25 cm	35 cm	5 cm	15 cm	25 cm	35 cm	5 cm	15 cm	25 cm
Density, g cm^{-3}	0.72	0.69	0.65	0.62	0.53	0.45	0.51	0.63	0.38	0.39	0.39
					Unimodal van Genuchten						
θ_s, cm^3 cm^{-3}	0.650	0.654	0.679	0.671	0.675	0.681	0.668	0.623	0.735	0.746	0.758
θ_r, cm^3 cm^{-3}	0.000	0.000	0.262	0.315	0.211	0.190	0.035	0.000	0.000	0.000	0.000
α, cm^{-1}	0.0538	0.0766	0.0405	0.0609	0.0644	0.1151	0.0515	0.0530	0.1933	0.0105	0.0051
n	1.105	1.123	1.265	1.364	1.323	1.222	1.114	1.108	1.114	1.154	1.190
m	0.095	0.110	0.209	0.267	0.244	0.182	0.102	0.098	0.102	0.134	0.159
					Multimodal van Genuchten						
	*-Bimodal for all soil samples at all depths except sample F at the 30 and 50 cm depth										
θ_s, cm^3 cm^{-3}	0.650	0.654	0.679	0.671	0.675	0.681	0.668	0.623	0.735	0.746	0.758
θ_r, cm^3 cm^{-3}	0.171	0.187	0.249	0.262	0.185	0.146	0.167	0.181	0.185	0.110	0.085
w_1	0.38	0.435	0.515	0.58	0.48	0.495	0.32	0.34	0.46	0.19	0.15
α_1, cm^{-1}	0.0285	0.0300	0.0249	0.0394	0.0376	0.0580	0.0292	0.0381	0.0891	0.1051	0.0821
n_1	2.233	2.752	2.304	2.279	2.607	1.241	2.692	2.389	2.128	1.660	1.878
m_1	0.552	0.637	0.566	0.561	0.616	0.554	0.629	0.582	0.530	0.398	0.468
w_2	0.62	0.565	0.485	0.42	0.42	0.505	0.68	0.66	0.54	0.29	0.23
α_2, cm^{-1}	0.0003	0.0004	0.0005	0.0004	0.0004	0.0004	0.0011	0.0009	0.0008	0.0011	0.0001
n_2	1.498	1.563	1.510	1.519	1.738	1.454	1.274	1.343	1.450	2.184	1.794
m_2	0.332	0.360	0.338	0.342	0.425	0.312	0.215	0.255	0.310	0.542	0.443
w_3										0.52	0.62
α_3, cm^{-1}										0.0002	0.0006
n_3										1.521	1.654
m_3										0.342	0.395

*-At the 30 and 50 cm depth the trimodal fit was the best with θ_s fixed.

the nature of the pore system. In our work, we had 2-3 data points between saturation and pF 2.0 thus reducing the unreliability in the conductivity estimate.

IV. Results and Discussion

The measured retention data of all the six soil samples are presented in Fig. 2 and 3 together with the least squares fitted unimodal and multimodal retention models. Also, the coefficients of the various fitted retention functions are listed in tables 1 and 2. It was observed that all the samples have a bend at or near pF 2.0, especially in the case of the multimodal fit. Yamanouchi (1977) reported that the characteristics of Kuroboku soil is in the fact that there is a distinct bend observed at or near pF 2.0. The explanation given to this is that the water held between saturation and the neighborhood of pF 2.0 is mainly in the loose void between aggregates, and a greater part of that water has a property to be removed as gravity water. Also, Tokunaga et al. (1984) using soft X-ray projection in the study of some samples volcanic ash soil (including Kuroboku) and its void, observed that the energy of retention can reach pF 2.5 which is equivalent to a pore diameter of about 10μm.

Unlike the unimodal function, the multimodal function described the measured data of each sample at each depth accurately (Fig. 2 and 3), and it was observed that in each case the two functions represented fundamentally different pore systems. It was observed that all the Kuroboku soils (samples A-E) exhibited bimodal pore-size distribution at all the depth measurements with the exception of sample A at the 35 cm depth only, which showed a trimodal pore-size distribution. From table 1 both the primary and secondary pores contributed almost equally (see w_i values) to the prediction of conductivity up to the 25 cm depth in the case of sample A ; the contribution of secondary pores however diminished at the 35 cm depth but was such that it cannot be ignored (see Fig. 4). The rest of the Kuroboku soil samples exhibited bimodal pore-size distribution at all depths with various contributions from the secondary pores. According to Durner (1994), whereas the primary pore system is determined by the particle size distribution of a soil, the pore space between aggregates depends only on the packing and is therefore essentially independent of the soil texture. For this reason the existence and extent of secondary pore systems in aggregated soils poses a limitation to the success potential of regression methods that seek to predict hydraulic conductivity relationships solely from particle-size distributions. If the relative conductivity is therefore predicted from only the particle-size distribution there is bound to be errors arising from the neglect of the secondary pores.

Even though soil sample F is of mineral origin it is light (see ρ_b in Table 2), having characteristics almost similar to the volcanic ash soil which was removed from on top of it during reclamation. It was observed from figure 3 that the multimodal model described the measured data quite well while the unimodal model had a lot of deviations. Table 2 further shows that the 30 and 50 cm depths were characterized by trimodal pore-size distribution while the 10 cm depth was characterized by a bimodal one. It was also observed that the contribution of the secondary pores in the case of the 30 and 50 cm depths was little but cannot be ignored if a good fit to the measured data was desired.

Relative Conductivity

The estimated conductivity curves for all the soil samples are presented in Fig. 4 and 5. In Fig. 4 it was observed that the relative conductivity for the 35 cm depth of the sample was over-estimated in the dry range (unsaturated zone) under the van Genuchten-Mualem model combination (unimodal), and it was under-estimated in the saturation zone. The same trend was observed for the 15 cm depth of sample B (Fig. 4), and the 5 cm depth of sample C (Fig. 4). The relative conductivity for the 5,

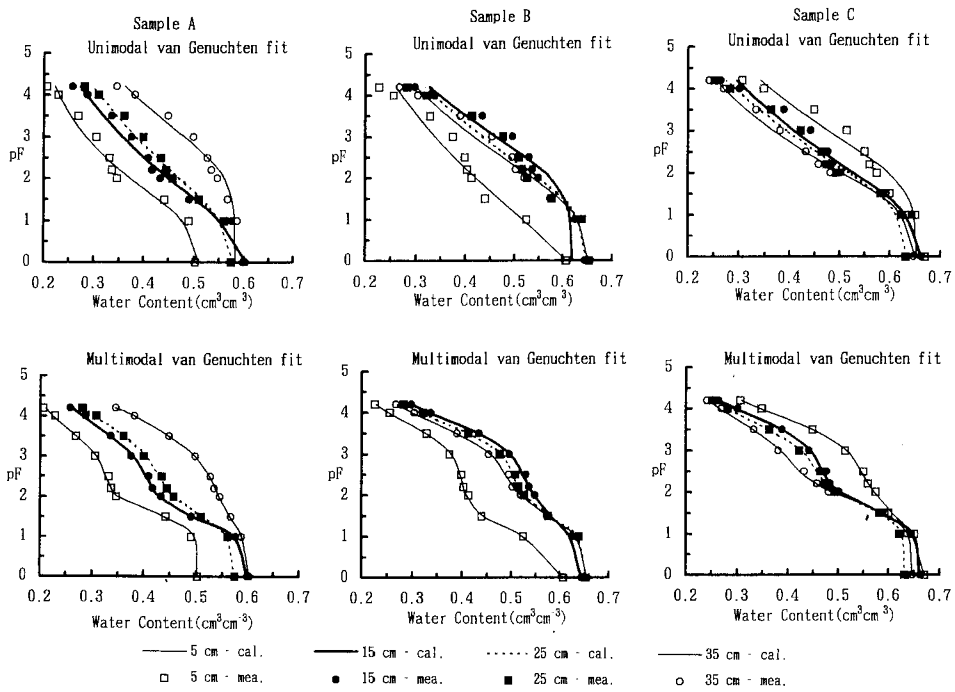

Fig. 2 Measured and fitted soil moisture release curves using the unimodal and multimodal van Genuchten models for Samples A-C.

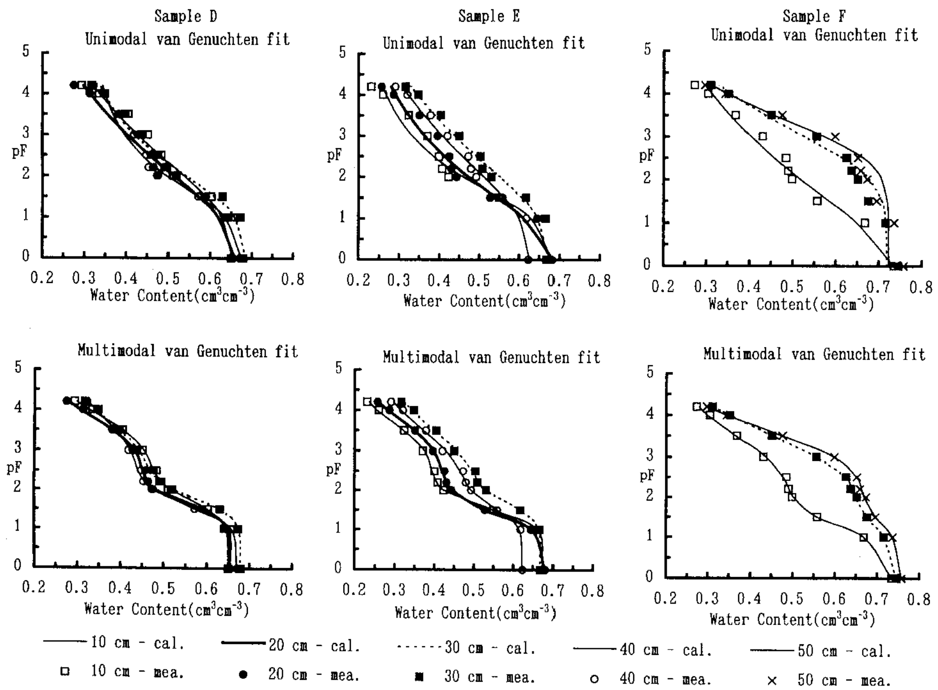

Fig. 3 Measured and fitted soil moisture release curves using the unimodal and multimodal van Genuchten models for Samples D-F.

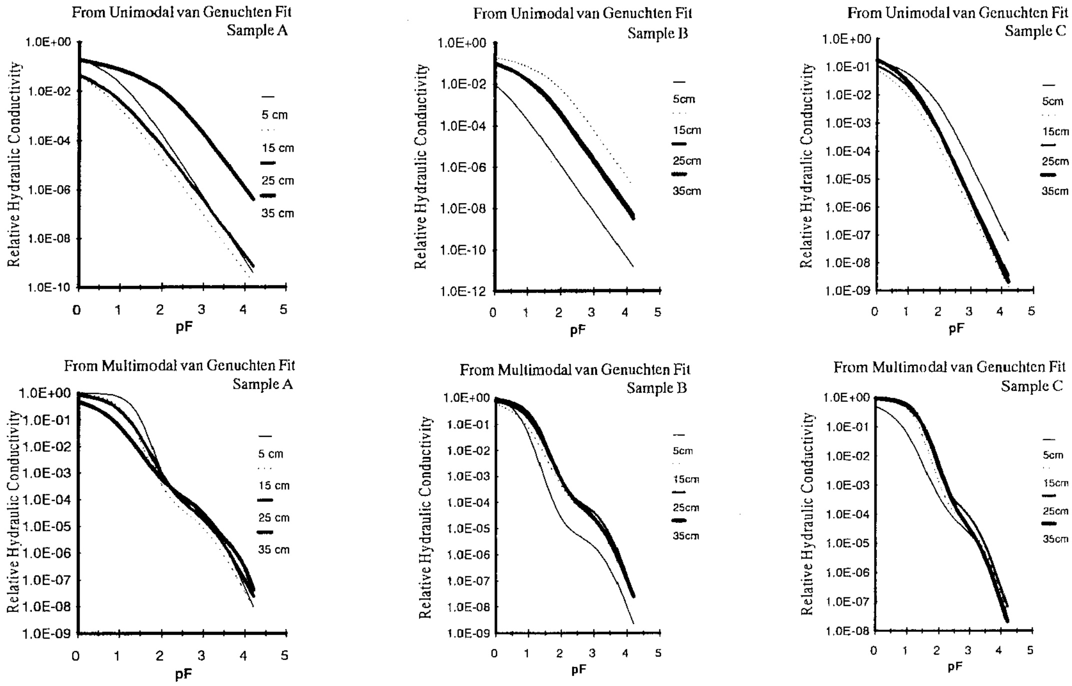

Fig. 4 Predicted relative conductivity function$K(h)$ from the unimodal and multimodal van Genuchten retention models for Samples A, B, and C.

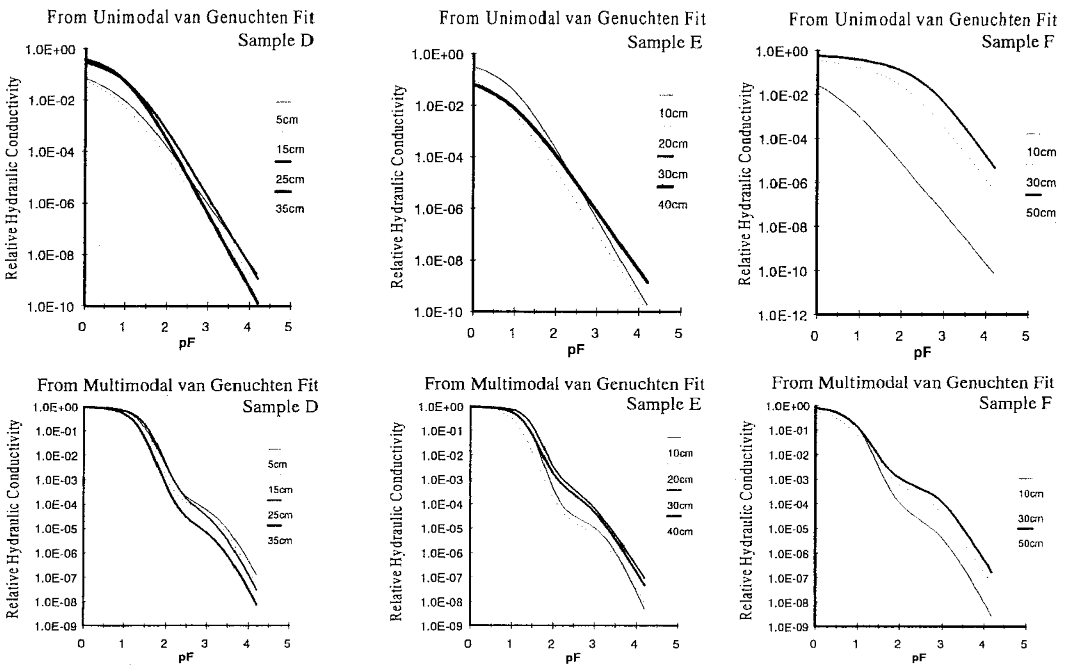

Fig. 5 Predicted relative conductivity function $K(h)$ from the unimodal and multimodal van Genuchten retention models for Samples D, E, and F.

15 and 25 cm depths of sample A were however under-estimated for in the whole range (from saturation to unsaturated zone) by applying the unimodal retention model. For the remaining Daisen Kuroboku soil samples, the relative conductivity predicted from the multimodal retention function was higher than that predicted from the unimodal function from saturation to the dry range. This was so even in the case where contribution from the secondary pores formed only a small fraction of the total pores. It follows that if the estimated conductivities from the unimodal model are used in simulation studies involving water movement through soils such as the samples used in this study, they are likely to lead to large errors.

It was also observed that the multimodal retention curves (Fig. 2 and 3) showed some similarity in shape to their corresponding conductivity estimates (Fig. 4 and 5). Using a hypothetical soil with a narrow textural pore-size distribution and a distinct secondary pore system, Durner (1994) observed two general findings : (1) the shape of the retention curve is directly reflected in the shape of the K(h) and, (2) the secondary pore system increases the conductivity by some orders of magnitude while taking only few percent of pore space. Our findings in relation to Daisen Kuroboku as explained above supports these two observations.

Even though sample F is not a volcanic ash soil, it was observed that the pore-size distribution included secondary pores which rendered the use of a unimodal model inappropriate. Since the sample is of mineral origin the very low bulk density values (Table 2) indicated a probability of aggregate formation, leading to a re-arrangement of the pore spaces. From Fig. 5, however, it was observed that the conductivity estimated from the unimodal model for the 30 and 50 cm depths were fairly good. In a strict sense therefore we could say that the pore system is unimodal (Durner, 1994), however, the curves cannot be adequately described by the classical sigmoidal retention model (see Fig. 3). The continuous, almost linear decrease of water content from pF 0 to 3.0 indicates a considerable pore density over a wide range of pore sizes, while the main pore system is located in the range of fine pores. A comparison of the conductivity estimated for these two depths from the unimodal and multimodal retention functions (Fig. 5) showed that at saturation they were almost of the same magnitude, but the conductivity estimated from the unimodal function becomes larger than that from the multimodal function immediately drainage starts and continues into the unsaturated zone.

Generally, by using the unimodal retention function the residual water content, θ_r of most of the samples were set to the boundary, i.e., zero (see Tables 1 and 2). According to Durner (1994), any influence of θ_r in unimodal hydraulic models is caused by interferences of the curve shape parameters. For the van Genuchten retention model, a decrease of the value of θ_r causes a shift of the parameter n toward a smaller value (near 1.0). Since the values of n for the samples used in this study were close to unity, it might be an indication of the failure of the unimodal model to describe the retention characteristics of the samples adequately.

V. Conclusion

We have shown that for a well-aggregated soil (e.g., Daisen Kuroboku) the commonly applied unimodal retention functions are insufficient for conductivity estimations because they lack the necessary flexibility in the range of large pores. Their use therefore in soil water movement simulations or parameter estimation where the inverse problem is solved may lead to wrong results (Durner, 1991). For aggregated soils, therefore, validation of hydraulic conductivity prediction methods should be reevaluated if the applied retention model did not accurately describe the data. Discrepancies found between estimates and measured data in some cases may not be due to the failure of the conductivity predictive model but the use of inadequate retention functions. If unimodal retention models are used to describe soils with wide pore-size distributions, they are forced to represent a non-negligible part of the pore space in the range of unrealistically large pore sizes. In such cases for example, the van Genuchten parameter n value is near unity and the conductivity prediction, especially near saturation becomes by definition unreliable.

Compared to the unimodal retention function, the use of the multimodal retention function improved the fit of the measured retention data and therefore led to a more reliable conductivity estimate. This conclusion was drawn from the shape of the predicted conductivity which resembled the soil moisture retention curve (i.e. "S"-shape), and the fact that at pF=0 the relative hydraulic conductivity was close to unity. With this kind of improvement water movement simulations in aggregated soils can be greatly enhanced.

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要　　約

土壌の不飽和透水係数の測定は難しく，より簡単に測定できる土壌水分特性曲線から推定する方法が良く用いられている。しかし，クロボクのような団粒化して孔隙が発達した土壌では，土壌水分特性曲線を表すのに一般に用いられている van Genuchten の関数ではうまく表現できないため，大きな誤差が生じる場合がある。本論文では，孔隙が発達した土壌の保水特性を表現するため Durner により改良された multimodal retention model と van Genuchten の unimodal retention model の両方法で大山クロボクの土壌水分特性曲線を表現し，Mualem の方法により不飽和透水係数を推定した。両モデルによる結果を比較すると，曲線の形状や unimodal retention model で見られた不合理な箇所が multimodal retention model では改善されていること等が分かった。

受稿日：平成7年 9 月 3 日
受理日：平成8年 6 月 28 日