IPEF n.48/49, p.50-60, jan./dez.1995

TRABALHO DE PESQUISA / RESEARH PAPER

HYDRAULIC PROPERTIES OF FOREST SOILS WITH MACROPORES IN LOW SUCTION ZONE

Masato Kobiyama[1]
Jumpei Kubota[2]
Yoshinori Tsukamoto

ABSTRACT - A new model for predicting the hydraulic properties of soils with macropores is proposed by making adjustments to the Brooks and Corey equations. The concept of "pseudo-saturation" was introduced to the equations and two new parameters, pseudo-saturated hydraulic conductivity, Kps, and pseudo-saturated water content, θ ps, are used in the proposed model. The comparison of the model with the experimental results from three geologically different forest soil samples showed good agreement between the measured and calculated data. Consequently it would be concluded that the new model is useful especially for forest soils because they have dominant macropore system. The size that defines the macropore is suggested to be 3 mm.

RESUMO - Um novo modelo para determinar as propriedades hidráulicas de solos com macroporos foi proposto através de ajuste das equações de Brooks e Corey. O conceito de "pseudo-saturação" foi introduzido às equações através de dois novos parâmetros, condutividade hidráulica pseudo-saturada (Kps) e umidade pseudo-saturada (θ ps). Comparando o modelo proposto com resultados experimentais de três solos florestais, foi obtida uma boa correlação entre os dados medidos e calculados. Conseqüentemente foi concluído que o modelo proposto é adequado para a obtenção das propriedades hidráulicas dos solos florestais. O tamanho que define o macroporo é proposto como 3 mm.

INTRODUCTION

Recently, the rainfall-runoff processes have been clarified through the development of physical hydrology (e.g., IKIRKBY, 1978) and forest hydrology (e.g., SWANK& CROSSLEY, 1988). In forest hydrology, the forest function in flood control and water resource conservation is stressed. It has been noted that the essence of the function is the existence of the forest soil itself (e.g., TSUKAMOTO & OHTA, 1987). As the forest promotes the formation of forest soils through the supply of organic matter and the activity of living organism, forest soils are strongly characterized by the presence of macropores.

BEVEN & GERMANN (1982) reviewed macropores and soil-water flow, and suggested that macropores play an important role in the hydrology of some field soils. It

[1] Departamento de Engenharia Sanitária e Ambiental, Universidade Federal de Santa Catarina - Caixa Postal 476, Trindade, 88010-970, Florianópolis, SC - Brasil;
[2] Department of Environmental Science and Resources - Tokyo University of Agricultures and Technology - Fuchu-city, Tokyo, 183, Japan.

means that the soil water regime in forest is usually influenced by the macropore system. Macropores may influence water flow especially at low suction values.

The objectives of this study are (1) to propose a simple model for estimating the hydraulic properties of soils that have macropores, by improving the equations of BROOKS & COREY (1964,1966), (2) to test the model with laboratory measurements of the hydraulic properties of undisturbed and compacted soils, and (3) to discuss the influence of macropores on the hydraulic properties.

This study adopts the concept of the macropores, proposed by SKOPP (1981), although various researchers have defined macropores and macroporosity. The concept is base on the function of pores on water movement and is more appropriate for hydrological studies. The size of the macropore will be defined after the discussion in this study.

THEORY

Equations for Soils not Containing Macropores

The hydraulic properties comprise saturated-unsaturated hydraulic conductivity and water retention. The former is expressed by the function between pressure head, ψ, and hydraulic conductivity , K, and the latter by that between pressure head and volumetric water content, θ.

As reviewed by NISHIGAKI (1983), various equations predicting the hydraulic properties have been proposed in soil physics and soil mechanics. The present study utilizes the equations obtained by BROOKS & COREY (1964, 1966) even though their equations include a discontinuity.

The Brooks and Corey equations are diagramed in FIGURE 1. The equation for hydraulic conductivity is

$$K = Ks \qquad \psi \geq \psi_b$$

$$K = Ks \times \left(\frac{\psi_b}{\psi}\right)^{\eta} \qquad \psi < \psi_b \tag{1}$$

where K (cm/s) is hydraulic conductivity, Ks (cm/s) is saturated hydraulic conductivity, ψ (cm) is pressure head, ψ_b (cm) is bubbling pressure head, and η is pore-size distribution index. The equation for water retention is

$$\theta = \theta s \qquad \psi \geq \psi_b$$

$$\theta = (\theta s = \theta r)\left(\frac{\psi_b}{\psi}\right)^{\lambda} + \theta r \qquad \psi < \psi_b \tag{2}$$

where θ is water content, θs is saturated water content, θr is residual water content, and λ is pore-size distribution index (η = 2 + 3 λ).

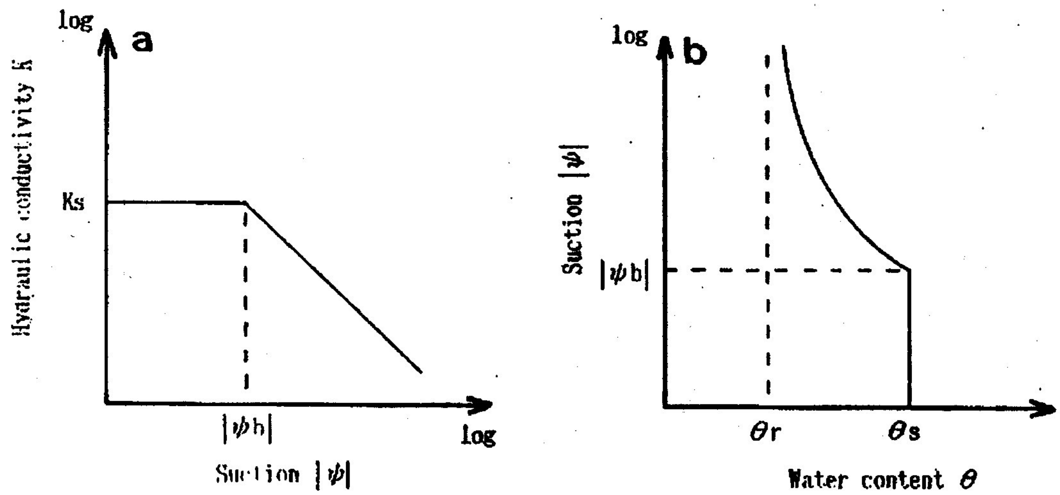

FIGURE 1. Diagrams of Brooks and Corey equations: (a) Hydraulic conductivity; (b) Water retention.

New Model by Addition to Brooks and Corey Equations

Using the results of their own as well as another study, GERMANN & BEVEN (1981) demonstrated that the value of saturated hydraulic conductivity was much larger than that of hydraulic conductivity which was nearly constant at lower suction values than the bubbling pressure suction (FIGURE 2). This constant value of hydraulic conducvity is assumed to be equivalent to the saturated hydraulic conductivity in common soils, i.e., soils without macropores. In the present study, this type of hydraulic conductivity is defined as "pseudo-saturated hydraulic conductivity", Kps. The pseudo-saturated hydraulic conductivity in FIGURE 2 is the saturated hydraulic conductivity of the soil matrix, not of the macropore system.

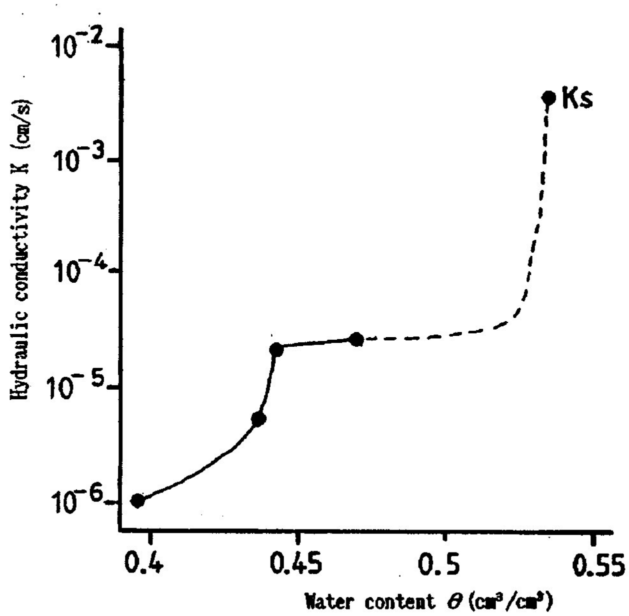

FIGURE 2. Hydraulic conductivity of a soil with macropore system (after Germann and Beven, 1981).

To predict water flow in a macropore system, the two-domain (macropore/ matrix) theory is used. BEVEN & GERMANN (1981) mentioned four models based on this theory. The present study, however, considers the soil matrix and macropores together, and treats them only with the Brooks and Corey equations by introducing the idea of "pseudo-saturation". The equation for hydraulic conductivity (eq.(1)) uses the pseudo-saturated hydraulic conductivity, Kps. In the same way, the water retention curve (eq.(2)) must be changed by using "pseudo-saturated water content", e ps.

The hydraulic properties of soils with macropores are mathematically expressed with the adjusted Brooks and Corey equations below (FIGURE 3).

Hydraulic conductivity

$$K = Ks \qquad \psi \geq 0$$

$$K = Kps \qquad 0 > \psi \geq \psi_b \qquad (3)$$

$$K = Ks \times \left(\frac{\psi_b}{\psi}\right)^{\eta} \qquad \psi < \psi_b$$

Water retention

$$\theta = \theta s \qquad \psi \geq 0$$

$$\theta = \theta ps \qquad 0 > \psi \geq \psi_b \qquad (2)$$

$$\theta = (\theta s - \theta r) \left(\frac{\psi_b}{\psi}\right)^{\lambda} + \theta r \qquad \psi < \psi_b$$

in the following, all soil hydraulic properties are expressed with the parameters of the adjusted equations.

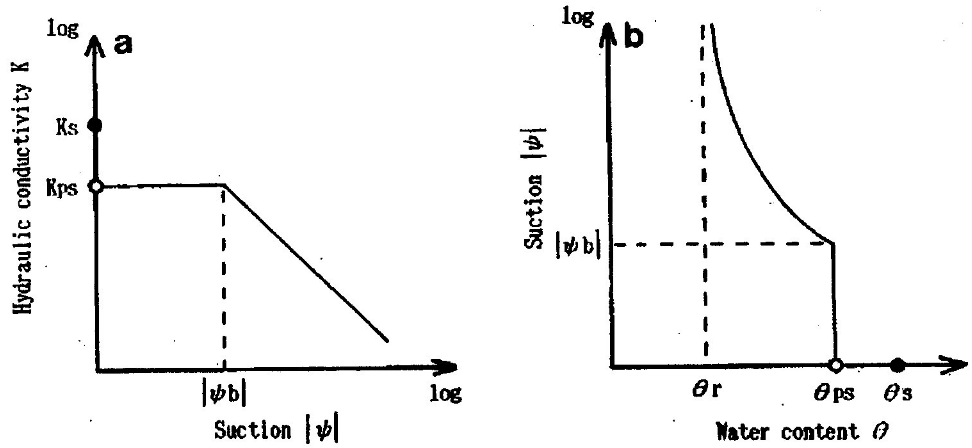

FIGURE 3. Diagrams of adjusted Brooks and Corey equations: (a) Hydraulic conductivity; (b) Water retention.

MATERIAL AND METHODS

Forest Soils Chosen For the Study

MOROTO & MASHIMO (1983) showed the reflection of parent material on physical properties (three-phase distribution, porosity, and permeability) of forest soils by studying Paleozoic, Tertiary, and granite soils. TSUKAMOTO & OHTA (1987) studied runoff processes on geologically different slopes (Tertiary, Paleozoic, and granite) in Japan, with depth of soil mantle and saturated hydraulic conductivity.

Because the effect of parent materials, principally Tertiary, Paleozoic, and granite, on soil formation has been often discussed in Japan, the present study also used these three geologically different forest soils. Soil samples on Tertiary rock were collected at the Rolling Land Laboratory, Tokyo Univ. of A. and T., in the Tama district of western Tokyo, soil samples on Paleozoicrocks at the University Forest, Tokyo Univ. of A. and T., in Gumma Prefecture (100 km northwest of Tokyo), and granite soil samples at the University Forest, Tokyo Univ., in Aichi Prefecture (FIGURE 4). The soils in all three areas are brown forest soils. Properties of the soil samples are listed in TABLE 1.

TABLE 1. Soil properties of the sampling areas.

Sampling Area	Parent material	Average specific gravity (g/cm^3)	Soil type
T	Mudstone, volcanicash, gravel (Tertiary)	2.67	B_D
M	Shale, sandstone, chert (Paleo-mesozoic)	2.75	B_D
G	Biotite granite, hornblende biotite granodiorite	2.75	B_D

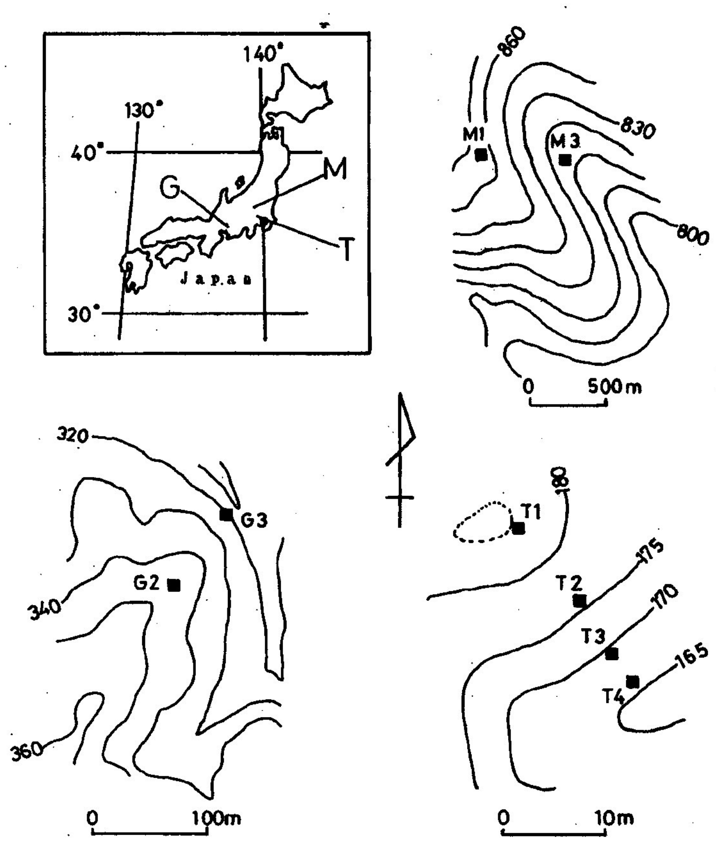

FIGURE 4. Location of the sampling points. T: Rolling Land Laboratory. Tokyo Univ. of A. & T. (Tertiary rocks and loam); M: University Forest. Tokyo Univ. of A. &T. (Paleo-Mesozoicrocks); G: University Forest. Univ. of Tokyo (Granite). The numbers indicate the sampling points.

Preparation of Soil Samples

ROGERS & CARTER (1987), OHTA & KATAGIRI (1988), and others studied the influence of the sampling technique and the sampler dimensions on the hydraulic properties of soil. The influence is due to the highly saturated condition and the existence of macropores. Therefore, a 400 cm^3 cylindrical, stainless steel sampler with a 113 mm diameter and a 40 mm height was used for all measurements of the saturated hydraulic conductivity of the undisturbed soils and for some of the measurements of the unsaturated hydraulic conductivity of the undisturbed soils. A 100 cm^3 sampler with a 50 mm diameter was used for the other measurements.

An undisturbed soil sample was taken by driving the sampler vertical into the soil at a depth of 15 cm. A heavy lubricant was applied to the inside wall of the sampler to ensure complete contact between the soil and the sampler wall. This sample is called the undisturbed type (U-type).

A disturbed (repacked) sample was made of the same soil material that was collected for the undisturbed sample. The collected soil was air dried and passed through a 2-mm sieve to remove stones. The sieved soil was packed as tightly as possible into the cylindrical sampler under water. In this operation, the densities of the soil samples were not controlled. This sample is called the air-dried and water-packed type (DW-type).

Saturated Hydraulic Conductivity

Measurement of the saturated hydraulic conductivity is based on the direct application of Darcy's law to a saturated soil column of uniform cross-sectional area. The constant head method was used for the U-type in a 400 cm 3 container and the falling head method for the DW-type in a 100 cm^3 container.

Unsaturated Hydraulic Conductivity

To measure the unsaturated hydraulic conductivity, the present study revised the method proposed by SHIOZAWA (1983) with reference to KLUTE (1986), and used the steady-state head control method.

Both 100-cm^3 and 400-cm^3 containers were used for the experiment. 3.0-mm diameter holes were made in six places around the 100-cm^3 sampler at 1.5 cm and 3.5 cm from the bottom in order to keep the soil air at atmospheric pressure during the unsaturated water content condition (the 400-cm^3 sampler had more holes). The container was covered with a cylindrical acrylic column to prevent evaporation and to hold the two ceramic tensiometers in place. The two ceramic tensiometers, with diameters of 3 mm and lengths the same as the container's radius, were used to measure the hydraulic head difference between two points between the two porous plates. The soil sample was held between two porous plates (preferentially wetted with water) that served to establish hydraulic contact with the water supply system connected to the inflow end and the removal system connected to the outflow end of the sample. Absorbent cotton was put between the sample and the porous plates to increase hydraulic contact. Three kinds of 3-mm thick d sks were used as the porous plates, because the bubbling pressure of the plates had to be at least as large as the magnitude of the most negative pressure head to be used during the measurements and because the plates require higher conductance than the soil sample. The hydraulic head distribution in the soil sample was controlled by a Mariotte bottle and a drip point. The water flowing from the drip point was collected in a bottle.

The conductivity function (K-ψ) was mapped through a series of steady-state flows with progressively decreasing values of ψ, beginning with ψ approximately equal to zero. The value of K when ψ is 0 cm is considered to be Ks and K measured when $0 > \psi > \psi_b$ is considered to be Kps.

Water Retention

To determine the retention function, the suction method was used with reference to KLUTE (1986). The soil sample, in a 100 cm^3 sampler without holes, was held between two end-caps. The bottom cap contains a porous ceramic plate. The porous plate, the sampler, and the caps were sealed together by O-rings. The lower end of the sample was connected to a reservoir bottle or a pressure regulator with a tube. The height difference between the reservoir and the sample created suction in soil water till pF 1.5. The pressure regulator was used to create greater suction in the soil water.

Measurements were taken at pressure heads of 0 cm of water, -3cm (= pF 0.5), -5cm (pF 0.7), -10cm (pF 1), -20cm (pF 1.3), -32cm (pF 1.5), -50cm (pF 1.7), -100cm (pF 2), -200cm (pF 2.3), -316cm (pF 2.5), -501cm (pF 2.7). In theory, the largest pores in the soil should drain first, followed by successively smaller and smaller pores.

The sample was weighed at each equilibrium. At the final equilibrium (pF 2.7), the water content of the sample was determined, and the water contents at ali the pressure heads were obtained by back-calculation using the changes in weight. Using the proposed model, the values of 8 when $\psi = 0$ and when $0 > \psi > \psi$ are considered to be θs and θps, respectively.

RESULTS AND DISCUSSION

Comparison of Ks-Kps Difference Between Undisturbed and Compacted Soils

TABLE 2 lists the results of the hydraulic conductivity experiment. The adjusted equation for hydraulic conductivity (eq.(3)) was compared with the graphs obtained from the measurement of unsaturated hydraulic conductivity using the 100-cm^3 containers in order to determine the parameters of Kps, ψ_b, and η for each sample. The values of Ks in TABLE 2 were determined by the measurement of saturated hydraulic conductivity using 400-cm^3 containers for U-type samples and 100-cm^3 ones for DW-type samples. The value of Ks is much larger than that of Kps for the undisturbed soils (U-type) while the values of Ks and Kps are nearly equal for compacted soils (DW-type). From the stand point that compacted soils have no macropore, it is assumed that the difference between Ks and Kps is due to the existence of macropores in the soil.

TABLE 2. Parameter values on hydraulic conductivity

Sample	Weight ($g/100cm^3$)	Ks (cm/s)	Kps (cm/s)	$\lvert\psi_b\rvert$ (cm)	η
T1-U		6.02x10-2			
T1-U			1.43x10-3	10.5	2.16
T1-DW	70.11		2.70x10-6	130	3.36
T1-DW	75.21	4.34x10-7			
T2-U		1.40x10-1			
T2-U			1.15x10-3	12.8	3.69
T2-DW	108.37		1.00x10-5	54	2.59
T2-DW	111.82		2.33x10-6	110	3.36
T3-U		5.25x10-2			
T3-U			1.48x10-2	4.6	3.85
T3-DW	119.02		1.30x10-7	145	3.79
T3-DW	118.12	3.13x10-7			
T4-U		1.12x10-1			
T4-U			1.90x10-3	5.2	3.15
M1-U		4.79x10-2			
M1-U			1.71x10-3	8.5	2.84
M1-DW	98.74		2.17x10-7	180	4.31
M1-DW	98.43	7.77x10-7			
M3-U		9.15x10-2			
M3-U			3.20x10-3	13	3.95
M3-DW	90.31		5.20x10-6	163	6.04
M3-DW	84.90		5.30x10-6	135	7.55
M3-DW	91.30	6.88x10-6			
G2-U		1.51x10-2			
G2-U			5.65x10-4	12.1	2.60
G2-DW	156.35		2.78x10-6	95	2.76
G2-DW	158.99		2.70x10-6	140	6.07
G2-DW	165.79	3.06x10-6			
G3-U		3.68x10-2			
G3-U			1.58x10-2	5.7	3.30
G3-DW	156.61		3.00x10-6	90	3.37
G3-DW	162.92	1.29x10-6			

T1-U = U-type sample at sampling point T1

Relationship of Ks and Kps

TABLE 2 includes the measured values for both saturated and unsaturated hydraulic conductivities. The measurements of both conductivities for one sample were conducted using only the apparatus for unsaturated hydraulic conductivity. The results for three samples, T1-U, T2-U, and T3-U, are plotted in logarithm graphs (FIGURE 5). For convenient the data for Ks are plotted on the vertical axis (K axis). FIGURE 5 shows that Ks is larger than Kps by two orders in each case. The measurements of T1 and T2 were carried out with a 400 cc container and that of T3 with a 100-cm^3 one. For unsaturated hydraulic conductivity, the dimensions of the container are considered to influence the determined values less than that for saturated hydraulic conductivity. This study could not measure the values of the conductivity in the suction range from 0 to 1-cm, after measuring the value of Ks. As demonstrated by GERMANN & BEVEN (1981), the function between K and ψ is continuous in practice, although the proposed model for soils containing macropores includes the discontinuity in the function. The next problem is to predict the function within the very low suction range from 0 to 1-cm. The proposed model (eq. (3)) produced good results from the experiments. It is, therefore, thought that the proposed model with the idea of "pseudo-saturated conductivity" is valid for solids containing macropores.

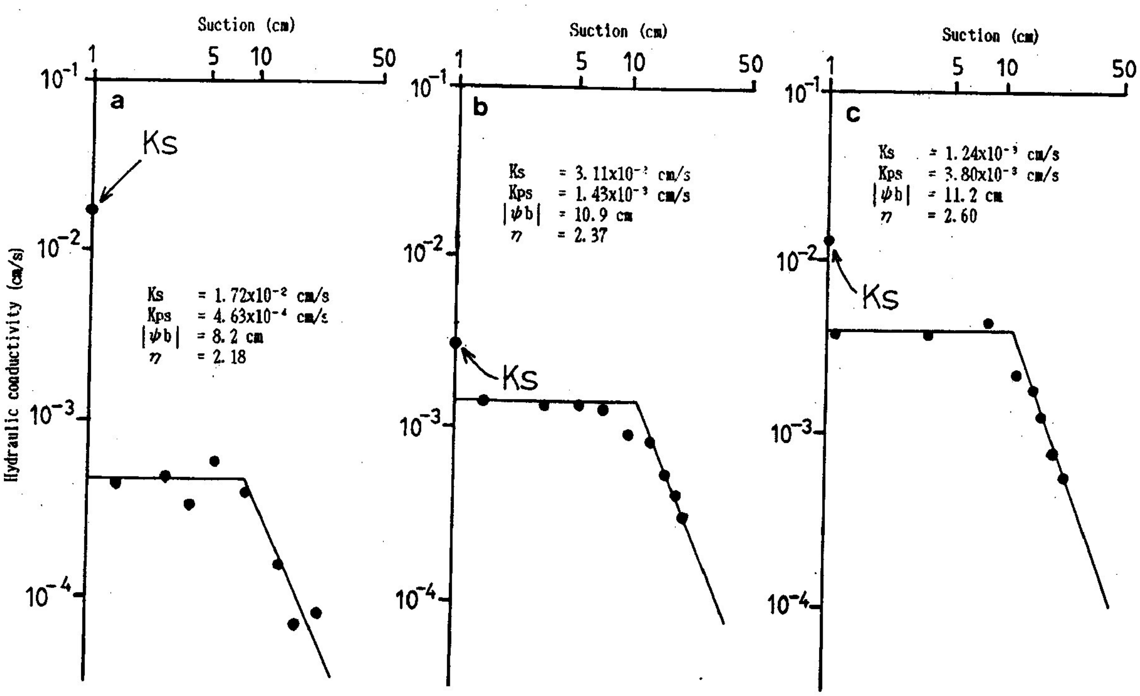

FIGURE 5. Hydraulic conductivities in low suction zone: (a) T1-U (400 cm^3); (b) T2-U (400 cm^3); (c) T3-U (100 cm^3).

Water' Retention

Two water retention examples. G2-U and G2-DW are plotted in semilog graph as water content is a function of suction (FIGURE 6). For convenient water content at suction equal to 0-cm is plotted on the horizontal axis (θaxis). λ and ψb were determined by eye and the lines were drawn. Applying the adjusted equation (eq.(4)) to the graphs, all the parameters in the equation were determined. Listing the results of the water retention experiment, TABLE 3 shows the remarkable difference between θs and θps for undisturbed soil (U-type), while the difference is only 0.01 for DW-type samples and is assumed to be experimental error. It can be, therefore, said that there is a difference within the U-type samples and not within the DW-type ones. The good prediction of the water retention function shows that the proposed version of the Brooks and Corey equations has validity.

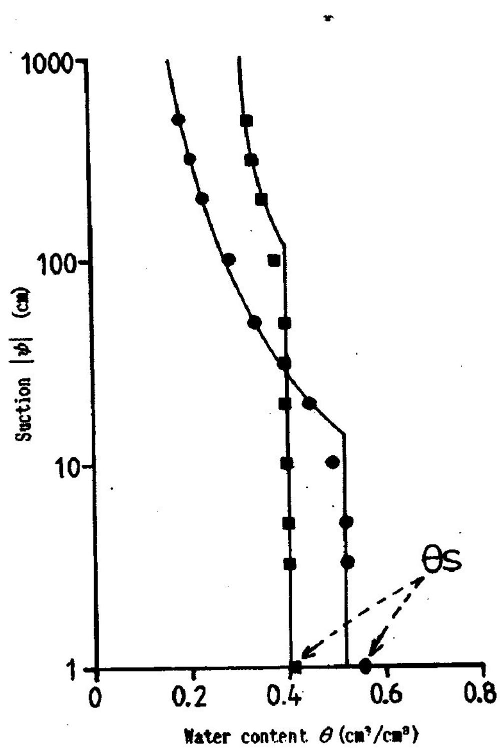

FIGURE 6. Relationship between water content and suction for samples G2-U and G2-DW ●: U-type (G1-U); ■: DW-type (G1-DW)

TABLE 3. Parameter values on water retention.

Sample	Weight ($g/100cm^3$)	θs (cm/s)	θps (cm/s)	θr	$\lvert\psi_b\rvert$ (cm)	λ
T1-U	43.05	0.84	0.74	0.31	16	0.58
T1-DW	60.14	0.76	0.75	0.55	120	0.40
T1-DW	63.02	0.77	0.76	0.68	160	1.00
T2-U	65.05	0.79	0.69	0.36	5.0	0.65
T3-U	75.91	0.69	0.62	0.31	5.7	0.69
T3-DW	110.26	0.58	0.57	0.50	78	0.97
M1-U	65.73	0.75	0.68	0.33	7.3	0.38
M1-DW	86.71	0.70	0.69	0.35	180	0.60
M1-DW	86.89	0.65	0.63	0.53	150	1.20
M3-U	54.03	0.76	0.71	0.35	4.8	0.40
M3-DW	72.71	0.70	0.68	0.49	68	0.95
G2-U	114.60	0.57	0.52	0.11	14	0.44
G2-DW	150.62	0.41	0.40	0.31	120	1.20
G2-DW	160.05	0.37	0.36	0.32	100	0.60
G3-U	108.45	0.60	0.50	0.15	12	0.76
G3-DW	145.83	0.47	0.46	0.34	125	1.00

Macroporosity and MaCropore Size

In the study by GERMANN & BEVEN (1981), the volume contents of the macropore system of two samples were 0.01 and 0.045. In the present study, the values of θs - θps vary from 0.05 to 0.10. It was assumed that values up to 0.02 were experimental error. Considering the error, the undisturbed samples used in the study have a macroporosity of 0.03 ~ 0.08.

Using the theory of capillary rise in a tube (the Laplace equation), gives the following equation;

$$D = -\frac{0.3}{\psi} \qquad (5)$$

where D (cm) is the diameter of a pore considered to be a cylindrical pore and ψ (cm) is the pressure head.

FIGURE 5(c) shows that hydraulic conductivity has already decreased from Ks to Kps at suction = 1.1 cm. Considering the results of GERMANN & BEVEN (1981), it is thought that hydraulic conductivity reaches the value of Kps at about suction = 1 cm after desaturation. As proposed by GERMANN & BEVEN (1981), an arbitrary value of ψ = -1.0 cm is used to indicate the boundary between macropores and soil matrix. From Equation 10, the equivalent diameter is 3 mm. The pore diameter of 3 mm divides soil porosity into two domains, macroporosity and matrix porosity, although SKOPP (1981) emphasized that size was an inadequate indicator. During the change of water content from θs to θps, the conductivity decreases from Ks to Kps very rapidly .This fact suggests that in a macropore with a diameter over 3 mm Darcy's law does not be hold. Even though the present study refers briefly to a diameter of 3 mm, it seems that a pore diameter of about 3 mm has an important significance for hydraulic properties of soils. It was found no difference between the values of Ks and Kps and between θs and θps when the diameters of all the pores were less than 3 mm.

Limitation of The Proposed Model to Simulate Field Soil Water Regime

BOUMA & RAA TS (1985) discussed by pass flow caused by vertical flow of free water through continuous macropores through unsaturated soil horizons. When water is applied to the soil matrix and if the water flux is greater than the absorbing capacity of the matrix, flow into the macropores occurs (BOUMA, 1990). This phenomenon was demonstrated in the field by BOUMA et al. (1981). The proposed model does not take bypass flow into consideration, and therefore has validity only when the soil matrix can absorb the applied water without by pass flow. Because of this, it can be said that the model has a static aspect.

CONCLUSION

The proposed model (eqs.(3) and (4)) for estimating soil hydraulic properties was compared with the results of the laboratory measurement of hydraulic conductivity and water retention. There was good agreement between the model and the experimental data. The present study emphasizes the need to introduce the concept of "pseudo-saturation" for prediction of the hydraulic properties of soils with macropores. Although the Brooks and Corey equations were used, other equations (e.g., MUALEM, 1976, and VAN GENUCHTEN, 1980) may be used with the introduction of θps and Kps. The proposed model would be useful for analyzing forest soils because they have dominant macropore systems. In the proposed model, 85 and Ks are equal to eps and Kps, respectively, for soils without macropores.

Further work is needed to estimate the functions of both hydraulic conductivity (K - ψ) between Ks and Kps and water retention (θ - ψ) between θs and θps.

REFERENCES

BEVEN, K. & GERMANN, P. Macropores and water flow in soils. **Water Resour. Res**., Washington, 18: 1311-25, 1982.

BOUMA, J. Using morphometric expressions for macropores to improve soil physical analyses of field soils. **Geoderma**, Amsterdam, 46: 3-11, 1990.

BOUMA, J & RAATS, P.A.C. (Editors) **Water and solute movement in heavy clay soils**. Proc. ISSS Symp. Wageningen, ILRI, 1985. 363p.

BOUMA, J. et al. A field method for measuring short-circuiting in clay soils. **J. Hydrol**., Amsterdam, 52: 347-54, 1981.

BROOKS, R.H. & COREY, A.T. Hydraulic properties of porous media. Fort Collins, Colorado State University, 1964. p.1-27 (Hydrology Paper n. 3).

BROOKS, R.H. & COREY, A.T. Properties of porous media affecting fluid flow. **J. Irrigation and Drainage Div**., Proc. ASCE , New York, 92(IR2): 61-88, 1966.

GERMANN, P. & BEVEN, K. Water flow in soil macropores: 1 - An experimental approach. **J. Soil Sci.**, Oxford, 32: 1-13, 1981.

KIRKBY, M.J. (Editor) **Hillslope hydrology**. New York, John Wiley, 1978. 323p.

KLUTE, A. (Editor) **Methods of soil analysis: 1-Physical and mineralogical methods**. 2.ed. Madison, Am. Soc. Agron., 1986. 1199p. (Agronomy Monograph 9).

MOROTO, K. & MASHIMO, Y. Forest soils in the hilly zone of Central Japan: 1-Physical properties. **Jap. J. For. Environment**, Tokyo, 25: 10-5, 1983.

MUALEM, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. **Water Resour. Res**., Washington, 12: 513-22, 1976.

NISHIGAKI, M. Some aspects on hydraulic parameters of saturated-unsaturated regional ground-waterflow. **J. Jap. Soc. Soil Mechanics and Foundation Engineering**, Tokyo, 23(3): 165-77, 1983.

OHTA, T. & KATAGIRI, M. Measurement of the saturated hydraulic conductivity of forest soil with a large-scale sampler: 1. **J. Jap. For. Soc.,** 70: 367-70, 1988.

ROGERS, J.S. & CARTER, C.E. Soil core sampling for hydraulic conductivity and bulk density. **Soil Sci. Soc. Am. J.,** Madison 51: 1393-4, 1987.

SHIOZAWA, S. Measurement method and accuracy for unsaturated hydraulic conductivity by the steady-state method. Trans. **Jap. Soc. Irri Drain. Reclam**, Tokyo, 106: 73-9, 1983.

SKOPP, J. Comment on "Micro-, meso-, and macroporosity of soil". **Soil Sci. Soc. Am. J.,** Madison, 45: 1246, 1981.

SWANK, W.T. & CROSSLEY, Jr., D.A. (Editors) **Forest hydrology and ecology at Coweeta** .New York, Springer-Verlag, 1988. 469p.

TSUKAMOTO, Y. & OHTA, T. Hillslope topography and runoff process on steep forested slopes. In: US-JAPAN SEMINAR ON HYDROLOGY, Hawaii, 1987. **Proceedings**. s.i., s.n., 1987. p.37-55.

VAN GENUCHTEN, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. **Soil Sci. Soc. Am. J.** , Madison, 44: 892-98, 1980.

Trabalho recebido = 10/10/1993
Trabalho aceito = 19/12/1994