NEW METHOD FOR DETERMINING HYDRAULIC PROPERTIES OF UNSATURATED SOIL USING EVAPORATION DATA

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Solving soil unsaturated flow problems requires knowledge of the water retention $\theta(\psi)$ and unsaturated hydraulic conductivity $k(\theta)$ relationships. This study introduces a new evaporation method for simultaneous estimation of both retention and unsaturated hydraulic conductivity data. Newton-Raphson iterative method was used to solve non-linear equations in time. Simultaneous transport of liquid and vapor flow in the unsaturated soil was modeled. Evaporation from a vertical column of soil material (tile) was simulated. Hydraulic parameters were estimated by minimizing the sum of squared differences between measured and simulated evaporation rate through the whole period of the experiment. Two laboratory experiments were carried out on the same sample under different conditions to evaluate the ability of this new method to provide good estimation of the retention and unsaturated conductivity curves. The results show that this method is stable, accurate, and can be applied for other types of soil.

***Key Words** : Evaporation, hydraulic properties, unsaturated soil material*

1. INTRODUCTION

Many laboratory and field methods exist to determine soil hydraulic properties, especially for the unsaturated hydraulic conductivity. Most methods remain relatively time consuming and costly, and are often limited to relatively narrow ranges of water content. Many attempts have been made to develop, improve or compare methods for measuring hydrodynamic properties in the laboratory. Stotle et al.[1] compared the applicability ranges and results of six laboratory methods (hot air, sorptivity, crust, drip infiltrometer, one-step outflow, and Wind's evaporation methods) for determining hydraulic conductivity. One main difference among the methods was the applicable range for pressure head and water content. Although inverse solution techniques are now routinely used for estimating unsaturated soil hydraulic functions from laboratory outflow experiments[2),3),4)], identifiability, uniqueness, and stability of the results are often in question.

Recently, two methods of measurement were extensively developed: one for the near-saturated zone and the other for drier conditions. Tension infiltrometers are now widely used in the first method for estimating the hydraulic conductivity of soils across the range from saturation to a suction head of typically -100 mm[5),6),7),8)]. With regard to the second method, i.e., for drier conditions, Wind[9)] developed a simple method for determining both the water retention and the unsaturated hydraulic conductivity relationships of soil samples in the laboratory and under evaporation conditions. When tensiometric measurement errors were taken into account, estimation of the water retention curve using the evaporation method was not very sensitive to experimental errors, but small uncertainties in tensiometric data influenced greatly the hydraulic conductivity determined under wet conditions[10),11)].

The purpose of this study is to present a new evaporation method for determining hydraulic properties of unsaturated soil. Unlike the previous methods, we need not to use tensiometers to measure the pressure head through the length of the sample. Thus, tensiometer measurement errors (errors due to the positions of the tensiometers in the soil and errors in the calibration of the tensiometers) were avoided. The accuracy and properties of the method were investigated.

2. THEORY

(1) Evaporation from a wet soil column

If the surface of a soil column were wet, and water loss were measured as a function of time, the evaporation rate would stay nearly constant for some time, and then suddenly decrease[12)]. Three stages of drying are often identified. During the first stage, the evaporation rate is relatively constant. The soil surface is wet, and the evaporation rate is determined entirely by the vapor concentration difference between the surface and the air, and the boundary layer resistance of the air above the soil surface. When the soil dries sufficiently that water can not be supplied to surface fast enough to meet the evaporation demand, the soil surface dries and the evaporation rate is reduced. The reduction is caused by the increased diffusion resistance of the dry soil which is between the wet soil and the atmosphere. As the depth of the dry layer increases, the evaporation rate decreases. The third stage of drying is often identified when the rate of decrease of evaporation with time becomes small. When the potential evaporation rate (E_p) is known, the vapor flux at the soil surface (q_{vs}) at any time can be calculated from[12)]:

$$q_{vs} = E_p \frac{(h_s - h_a)}{(1 - h_a)} \qquad (1)$$

where h_s is the humidity of the soil surface and h_a is the atmospheric humidity. Following first stage drying, q_{vs} can be calculated from change in profile water content of the soil. It can be analyzed as a vapor diffusion problem and/or as a liquid flow problem. An accurate analysis, however, must take into account both liquid and vapor flow.

(2) Governing flow equations

Simultaneous transport of both liquid and vapor in isothermal soil was considered in this study.

a) Liquid-phase transport

Under most conditions, vertical liquid flow in unsaturated porous media is described by the Darcy-Buckingham equation:

$$q_l = -k\left[\left(\frac{\partial \psi}{\partial z}\right) + 1\right] \qquad (2)$$

where q_l is the unsaturated water flux ($kg\ m^{-2}\ s^{-1}$), k is the soil hydraulic conductivity ($kg\ s\ m^{-3} \cong 0.98\ cm\ s^{-1}$), ψ is the soil matric head (≤ 0, $J\ kg^{-1}$), and z is the vertical coordinate (m, positive upward). For reasons of analytical tractability the Campbell[13)] relationships for soil water retention and hydraulic conductivity characteristics are used here:

$$\theta = \theta_{sat}\left(\frac{\psi_e}{\psi}\right)^{1/b} \qquad (3)$$

$$k = k_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{m} \qquad (4)$$

where θ is the soil volumetric water content ($cm^3\ cm^{-3}$), θ_{sat} is the saturated soil water content or porosity ($cm^3\ cm^{-3}$), ψ_e is the air entry potential ($J\ kg^{-1}$), b is a soil parameter (defined as the slope of a $\log\psi$ versus $\log\theta$ plot), k_{sat} is the saturated hydraulic conductivity ($kg\ s\ m^{-3}$), and m=2b+3. In general, when the soil becomes more sandy, ψ_e becomes less negative, and k_{sat} and b^{-1} become larger[14)].

b) Vapor-phase transport

The flux density of vapor (q_v) in isothermal soil is described by Fick's law[12)]:

$$q_v = -D_v \frac{dc_v}{dz} \qquad (5)$$

where c_v is the soil vapor concentration ($c_v = c_v^* h_r$, $g\ m^{-3}$, h_r is the relative humidity and c_v^* is the saturation vapor concentration at soil temperature) and D_v is the water vapor diffusivity in soil ($D_v = 0.66 D_o(\theta_{sat} - \theta)$, $m^2\ s^{-1}$, D_o is the diffusion coefficient for water in the air).

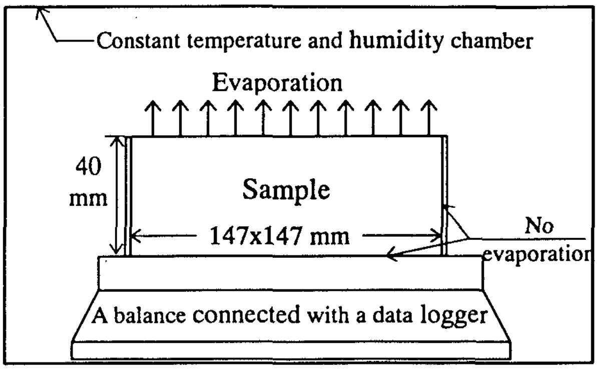

Fig. 1 The apparatus used for evaporation experiments.

The diffusivity of water vapor in the air depends on the temperature of the air, as well as its pressure. The following relationship is often used to express pressure and temperature dependence of diffusivity:

$$D_o\ (m^2\ s^{-1}) = \frac{2.12}{(10^5)}\left(\frac{T_s}{273.16}\right)^2\left(\frac{1013}{P}\right) \qquad (6)$$

where T_s is the soil surface temperature (K) and P is the pressure of the air (hPa). If the soil is isothermal, then $dc_v/dz = c_v^* dh_r/dz$ and Eq. (5) can be rewritten as:

$$q_v = -D_v c_v^* \frac{dh_r}{dz} \qquad (7)$$

The relative humidity of the air in the soil pore space expressed as a function, h_r, is a function of ψ, assuming that osmotic potential is insignificant:

$$h_r = \exp\left(\frac{\psi M_w}{RT_s}\right) \qquad (8)$$

where M_w is the molar mass of water ($0.018\ kg\ mol^{-1}$) and R is a universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$). Using the chain rule, $dh_r/dz = (dh_r/d\psi)(d\psi/dz)$. Applying in Eqs. (7) and (8), we get:

$$q_v = -D_v c_v^* h_r \frac{M_w}{RT_s}\frac{d\psi}{dz} = -k_v \frac{d\psi}{dz} \qquad (9)$$

where k_v is a vapor conductivity.

3. EVAPORATION EXPERIMENTS

The evaporation experiments were carried out in a controlled temperature and relative humidity chamber. A new type of ceramic tile using industrial wastes as a raw material has been used as a soil material sample. The tile has pores with an average size of about 10 micrometers and in saturated condition has a volumetric water content of 0.34 $cm^3\ cm^{-3}$. It has a dry density of $1.442(10^3)$ $kg\ m^{-3}$ and a saturated hydraulic conductivity of $1.2755(10^{-4})$ $kg\ s\ m^{-3}$. More explanation about the characteristics of this tile has been presented by Ozaki and Suzuki[15]. The dimensions of the used tile sample are LxWxH: 147x147x40 mm. Two laboratory experiments were done. The first experiment was carried out under an air temperature of 30 °C and a relative humidity of 40% while the second one was under a temperature of 25 °C and a relative humidity of 40%. At the beginning of each experiment the tile was fully saturated. During experiments, the tile was placed inside the chamber on the plate of a balance connected with a data logger (Fig. 1).

The boundary conditions were controlled to make a simple flow through the specimen. A plastic film covered the bottom and the vertical sides of the sample, so that the evaporation occurred only through the top surface of the sample. Weight of the sample was recorded periodically in order to determine the evaporation water loss with time. The evaporation experiments were stopped when the sample weight remained constant with time. While the first experiment was used to estimate the unsaturated hydraulic properties of the sample, the second experiment was used to check the reliability of this new method.

4. BACK-ANALYSIS TECHNIQUE USING EVAPORATION DATA

Figure 2 schematically shows the procedure of the used back-analysis technique, which can be summarized as follows:

(a) According to the properties and dimensions of the soil sample, we define θ_{sat}, k_{sat}, and the height of the soil sample (d);

(b) From experimental conditions, we input h_a and T_s;

(c) From the results of the experiment, we define E_p, the total time of the experiment (t_{exp}), and

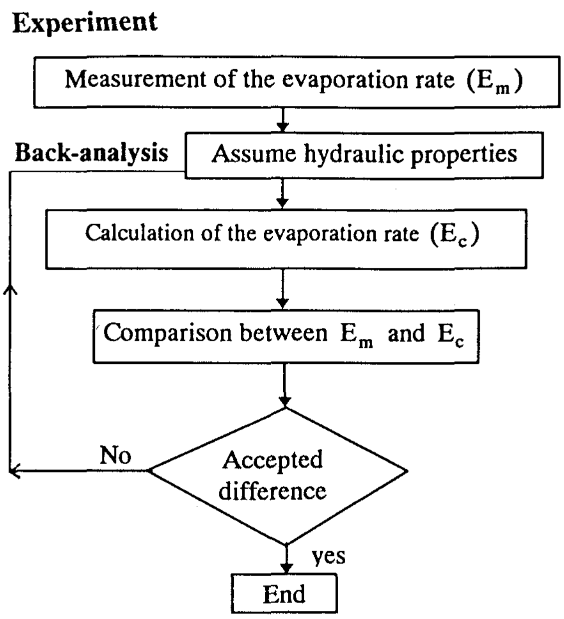

Fig. 2 Procedure of the back-analysis technique.

the transient change of the evaporation rate (E_m) which measured during t_{exp};

(d) According to a chosen value of time increment (Δt), we divide t_{exp} to n divisions ($n = t_{exp} / \Delta t$). The measured evaporation rate at the boundaries of all time divisions can be interpolated from the measured evaporation rate (E_{mi}, $i = 1,2,....,n+1$);

(e) An appropriate values of b and ψ_e are assumed;

(f) Newton-Raphson procedure is used to solve the non-linear equations in time by linearizing the differential equations in space. To apply this method, the mass balance for each node in the network must first be written. The mass balance of a thin layer of soil at a certain node includes the difference between the amount of water that flows into and out of the layer at its boundary (q_l, from Eq. 2), the difference between the amount of vapor that flows in and out of the layer (q_v, from Eq. 9), and the amount of the water that is stored there ($\rho_w \Delta z \Delta\theta / \Delta t$, ρ_w is the water density, Δz is the layer thickness, and $\Delta\theta$ is the change of the volumetric water content of the layer during Δt);

(g) Boundary conditions are easily applied in the Newton-Raphson solution scheme. For evaporation, the flux is subtracted as a sink term to the mass balance equation at the soil surface (node 1);

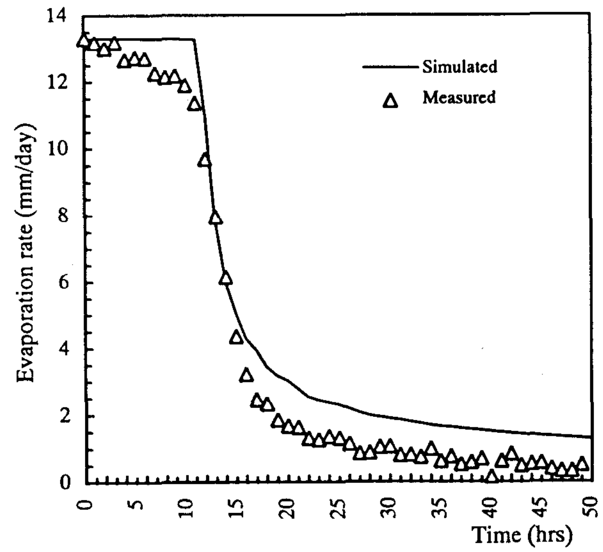

Fig. 3 Measured and simulated evaporation rate during experiment 1.

(h) New potentials, water contents, and conductivities at the end of each time step are calculated at each node. Also, the evaporation rate from the soil surface (E_c) is calculated;

(i) At the end of each run the measured flux densities of water evaporating from the surface of the profile (E_{mi}, $i = 1,2,... ,n+1$) and that calculated from change in profile water content (E_{ci}, $i = 1,2, ...,n+1$) are compared and the sum of squared differences is calculated; and

(j) If the summation of the squared differences is less than an accepted value the iterations are stopped. Otherwise, values of b and ψ_e are changed and processes (f) through (j) are repeated.

5. RESULTS AND DISCUSSION

Because this approach deals with an evaporation experiment, only hydrodynamic properties of a drying sample are estimated and hysteresis in the retention curve is not taken into account. Many calculations with changing the hydraulic properties of the tile were performed to minimize the sum of the square differences between the measured and the simulated evaporation rate during 50 hours of the first experiment. The fitted parameters for the used tile was found to be, the soil parameter, b=2.0 and the air entry value, $\psi_e = -9.60$ J kg^{-1}. The values of b and ψ_e locate in the range for typical soils, expected by Campbell[12]. Figure 3 shows a comparison between the measured and simulated

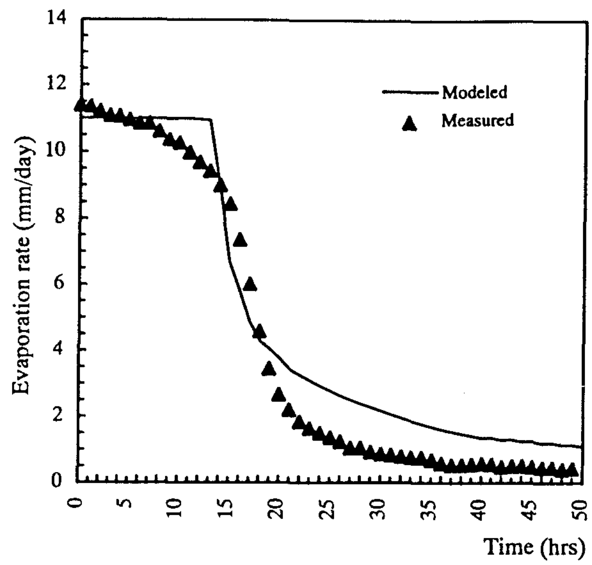

Fig. 4 Measured and modeled evaporation rate during experiment 2.

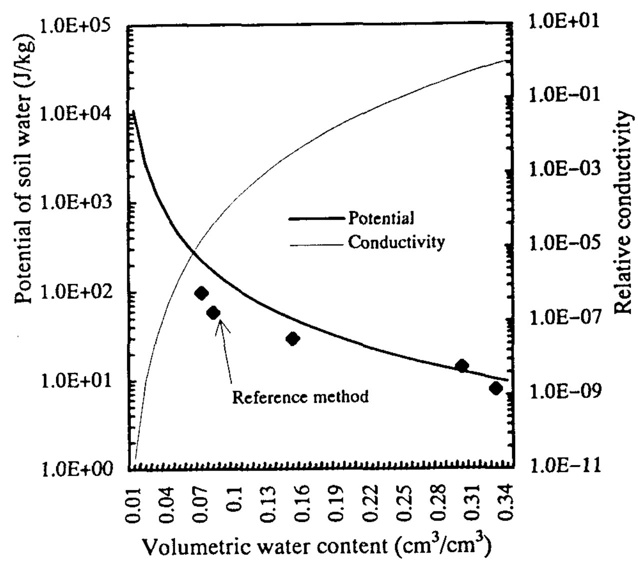

Fig. 5 Unsaturated hydraulic properties using the new evaporation method.

evaporation, during the time of experiment 1. As shown in this figure, the results are in good agreement. Also, from this figure it is observed that the first stage of drying continued for 11 hours with a potential evaporation rate of 13.3 mm/day. This means that around 44% of the total water of the saturated tile was evaporated to start the second stage of drying. As the evaporation experiment was carried out through a wide range of water content (from saturation to approximately dry soil), this implies that the proposed method results in soil hydraulic properties valid for a wide range of water content.

To check the reliability and the accuracy of the hydraulic properties that were obtained from experiment 1, the evaporation rate from experiment 2 was modeled using the same unsaturated hydraulic parameters (b and ψ_e) with changing the boundary conditions as those of experiment 2. Figure 4 shows a comparison between the measured and the modeled evaporation during the time of experiment 2. It is clear that the agreement is well and the proposed method succeeded to make an accurate estimation of the hydraulic properties. As shown in this figure that the first stage of drying took 13 hours with $E_p = 11.0$ mm/day consuming 44% of the stored water in the tile at the beginning of the experiment.

With the values of the hydraulic parameters (b and ψ_e), we could calculate the soil-water characteristic curve $\theta(\psi)$ and the unsaturated hydraulic conductivity curve $k(\theta)$. The results are plotted as shown in Fig. 5. Also, other results from a reference method, which required the direct measurement of ψ and θ for each point, are plotted on the same graph. It is clear that, the soil water characteristic curves determined with this method and those points obtained from the reference method are close.

Figures 6 and 7 illustrate volumetric water content and matric potential profiles at different times during experiment 1, respectively. From the figures, it is clear that till 10 hours both of the profiles are almost constant through the depth of the sample. This period completely lies in the first stage of drying. After that, it is clear that a dry layer of soil is formed at the surface (the second stage of drying). Also, it is observed that, as the time increases the dry layer deepens, causing an increase in vapor diffusion resistance.

CONCLUSIONS

This study proposed a new and simple method for determining the unsaturated hydraulic properties (water retention curve and hydraulic conductivity). The new method needs only simple data and wears an aspect of certainty. In this method, we need not to measure the pressure head through the length of the sample, so the tensiometer measurement errors are avoided. The obtained unsaturated hydraulic parameters simulated the evaporation rate through a wide range of water content. The water retention curve obtained from the fitted parameters agreed well with the data of a reference method. In this

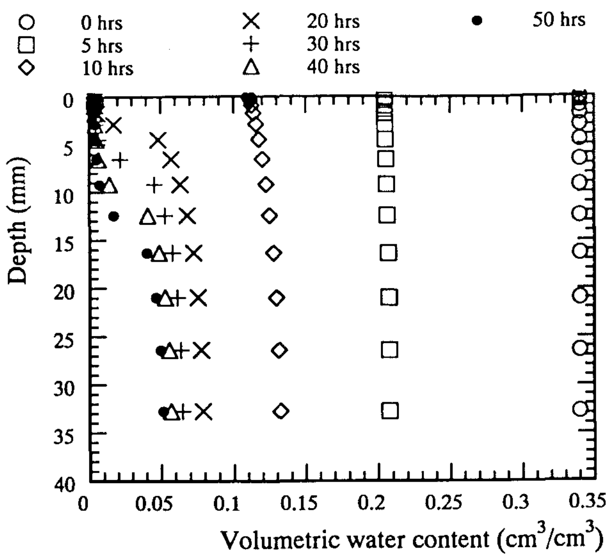

Fig. 6 Volumetric water content profiles at different times during experiment 1.

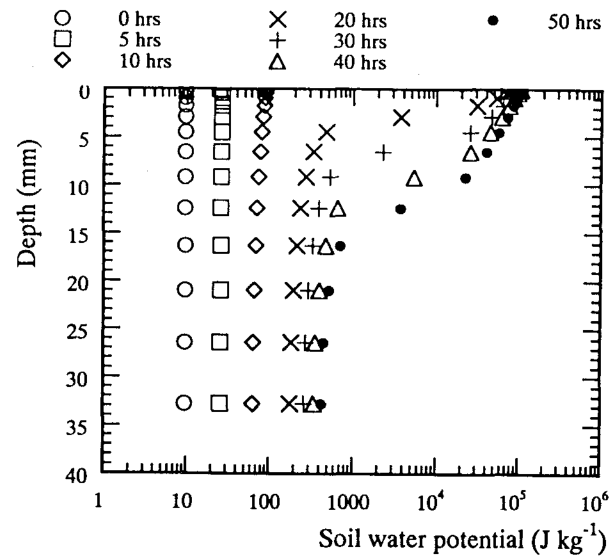

Fig. 7 Matric potential profiles at different times during experiment 1.

study, we showed that the estimated parameters can be successfully used to analyze the transient change of the evaporation rate from a soil sample under defined atmospheric conditions. By using this numerical model for unsaturated flow in two-phases, several questions related to the consequences of soil matric potential, hydraulic conductivity, and volumetric water content profiles through the time of the evaporation experiment were solved. The first stage of drying for this tile consumed 44% of the whole water of the saturated sample.

REFERENCES

1) Stotle, J., Freijer, J.I., Bouten, W., Dirksen, C., Halbertsma, J.M., van Dam, J.C., van den Berg, J.A., Veerman, G.J. and Wösten, J.H.M.: Comparison of six methods to determine unsaturated soil hydraulic conductivity, *Soil Sci. Soc. Am. J.*, Vol. 58, pp. 1596-1603, 1994.
2) Zachmann, D.W., Duchateau, P.C. and Klute, A: The calibration of the Richards flow equation for a draining column by parameter identification, *Soil Sci. Soc. Am. J.*, Vol. 45, pp. 1012-1015, 1981.
3) Dane, J.H. and Hruska, S.: In-situ determination of soil hydraulic properties during drainage, *Soil Sci. Soc. Am. J.*, Vol. 47, pp. 619-624, 1983.
4) Kool, J.B., Parker, J.C. and Van Genuchten, M.Th.: Determining soil hydraulic properties from one-step outflow experiments by parameter estimation: I. Theory and numerical studies, *Soil Sci. Soc. Am. J.*, Vol. 49, pp. 1348-1354, 1985.
5) Perroux, K.M. and White, I.: Designs for disc permeameters, *Soi. Sci. Soc. Am. J.*, Vol. 52, pp. 1205-1215, 1988.
6) Reynolds, W.D. and Elrick, D.E.: Determination of hydraulic conductivity using a tension infiltrometer, *Soil Sci Soc. Am. J.*, Vol. 55, pp. 633-639, 1991.
7) Logsdon, S.D. and Jaynes, D.B.: Methodology for determining hydraulic conductivity with tension infiltrometers, *Soil Sci. Soc. Am. J.*, Vol. 57, pp. 1426-1431, 1993.
8) Jarvis, N.J. and Messing, I.: Near-saturated hydraulic conductivity in soils of contrasting texture measured by tension infiltrometers, *Soil Sci. Soc. Am. J.*, Vol. 59, pp. 27-34, 1995.
9) Wind, G.P.: Capillary conductivity data estimated by a simple method. P. 181-191. *In* P.E. Rijtema and H. Wassink (ed.) Water in the unsaturated zone. Vol. 1. Proc. of the Wageningen Symp., Wageningen, the Netherlands. June 1966. Inst. Assoc. of Scientific Hydrology, Gentbrugge, Belgium/UNESCO Paris, 1969.
10) Tamari, S., Bruckler, L., Halbertsma, J.M. and Chadoeuf, J.: A simple method for determining soil hydraulic properties in the laboratory, *Soil Sci. Soc. Am. J.*, Vol. 57, pp. 642-651, 1993.
11) Mohrath, D., Bruckler, L., Bertuzzi, P., Gaudu, J.C. and Bourlet, M.: Error analysis of an evaporation method for determining hydrodynamic properties in unsaturated soil, *Soil Sci. Soc. Am. J.*, Vol. 61, pp. 725-735, 1997.
12) Campbell, G.S.: Soil physics with BASIC: Transport models for soil-plant systems, Elsevier, Amsterdam, Netherlands, 1985.
13) Campbell, G.S.: A simple method for determining unsaturated conductivity from moisture retention data, *Soil Sci.*, Vol. 117, pp. 311-314, 1974.
14) Kim, C.P., Stricker, J.N.M. and Torfs, P.J.J.F.: An analytical framework for the water budget of the unsaturated zone, *Water Resour. Res.*, Vol. 32(12), pp. 3475-3484, 1996.
15) Ozaki, T. and Suzuki, Y.: Study on the contribution of water-retentive ceramic tile to the reduction of environment heat accumulation, *Annual Journal of Hydraulic Eng. (in Japanese)*, Vol. 42, pp. 61-66, 1998.

(Received September 30, 1999)