Measurement of Unsaturated Ground Hydraulic Properties using a Dynamic State Soil Moisture Distribution Model

Mise en œuvre de l'évaluation d'une mesure des propriétés hydrauliques d'un sol non saturé par un modèle dynamique de distribution de l'humidité

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ABSTRACT: This paper presents a new in-situ test for producing a moisture characteristic curve and estimating unsaturated hydraulic conductivity using a reduced number of measurement parameters. Measurement parameters are restricted to determining the amount of infiltration and the pressure head, and can be used to determine the hydraulic properties of unsaturated soils. The model expresses the dynamic state of moisture distribution using a sigmoid function, and does not require measurement of the amount of soils moisture. Experimental results showed that suction of the moisture characteristic curve was small and estimated based on the influence of pore air pressure, and the values obtained for saturated and unsaturated hydraulic conductivity were in agreement with the results of laboratory tests.

RÉSUMÉ : Nous présentons ici la mise en œuvre d'une expérience in situ , destinée à définir une courbe caractéristique de l'humidité et la conductivité hydraulique d'un sol nonsaturé. Cette méthode, basée sur un modèle de distribution proposé par les auteurs a l'avantage d'éliminer un paramètre de mesure. Les paramètres de mesure nécesssaires pour déterminer la conductivité hydraulique du sol non saturé sont seulement le degré d'infiltration et la pression hydraulique du haut. Le modèle développé par les auteurs utilise une courbe sigmoïde de mesure de distribution de l'humidité dynamique, ceci permet de supprimer la mesure du taux d'humidité. Nous avons comparé la succion obtenue pour la courbe caractéristique d'humidité et observé qu'elle est un peu plus faible sous l'influence de la pression d'air des pores, mais nous pouvons conclure que nos résultats de conductivité hydraulique, en sol saturé et non saturé, sont comparables aux résultats expérimentaux en laboratoire.

KEYWORDS: Unsaturated soils, Hydraulic conductivity, In-situ test, soil water characteristic curve

1 INTRODUCTION

Hydraulic conductivity of the ground depends on the degree of saturation. Since boundary conditions vary, hydraulic conductivities in in situ tests are classified into four categories; unsaturated and saturated hydraulic conductivities of soils below the groundwater level, which are usually saturated, and unsaturated and saturated hydraulic conductivities of soils that are above the groundwater level, which are usually unsaturated. In embankments or slopes where groundwater levels are deep, soils are typically in an unsaturated state. However, intense rainfall and seepage water change the soil condition from being unsaturated to saturated. Consequently, the development of an in-situ test for evaluating the hydraulic properties of saturated and unsaturated soils is required. Current in situ permeability tests of unsaturated sediments require special equipment, and the method used to saturate the foundation in such tests is often difficult. These problems of soils have made it difficult to develop effective techniques for assessing the hydraulic characteristics of soils in practice.

This study therefore sought to develop a simple method for evaluating the hydraulic properties of foundations, which are typically unsaturated. This method only measures osmotic flow and pressure head, but it is capable of estimating hydraulic conductivity and producing a moisture characteristic curve of the unsaturated foundation by using a dynamic state moisture distribution model developed by the authors.

2 WETTING AND SATURATION FRONTS

In order to clarify the hydraulic properties of foundations in-situ, a simple examination method is desirable. A simple permeation examination was therefore used for increasing the degree of saturation of the foundation. Wetting fronts advance within foundations and increase the degree of saturation in permeation tests. Yong (1975) showed that the distance over which a wetting front advances in a one-dimensional lateral flow is proportional to the square root of time. They also observed that the relation was established under conditions of one-dimensional vertical flow. In this study, we referred to the depth of boundary that reaches saturation from being unsaturated in the one-dimensional vertical flow as the "saturation front" (Fig.1). We then used a numerical simulation to determine whether the square root of time could be applied to estimate the depth of the saturation front. The results of the numerical simulations are shown in Fig. 2.

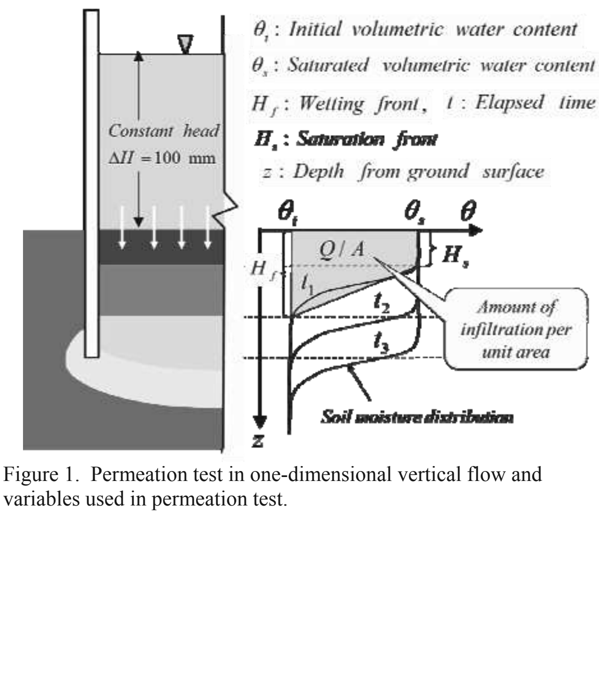

Figure 1. Permeation test in one-dimensional vertical flow and variables used in permeation test.

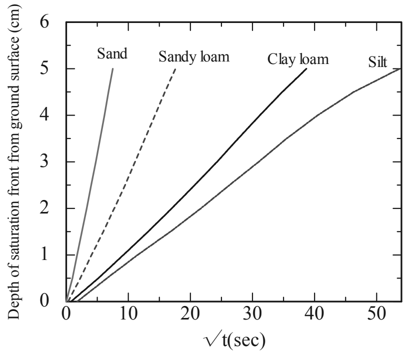

Figure 2. Depth of saturation front as a function of time.

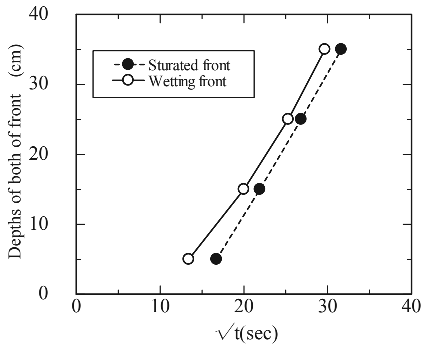

Figure 3. Observed depth of saturation front and wetting front as a function of time.

The numerical simulations showed that the depth of a saturation front was proportional to the square root of time when a constant water level of 10 cm was applied. It is considered that nonlinearity arouse in the second half of the experiment due to the presence of silt. Fig. 3 shows the experimental results obtained when water moving through sand was observed using four-point moisture sensors. Since the time of onset of watering is not clear, there is a gap in the range and time, but the results obtained by numerical simulation and in the experiments produced the same results.

These data show that shows that we can determine the depth of a saturation front using one proportionality factor and the following equation:

$$H_s = s\sqrt{t} \quad (1)$$

where, H_s is the depth of saturation front, t is elapsed time and s is the regression parameter.

3 OUTLINE OF PERMEATION TEST

3.1 *Experimental apparatus and measured parameters*

A soil chamber was used to imitate the experimental apparatus in-situ (Fig. 5). As shown in Fig. 4, the main part of the experimental apparatus has a Marriott tank and a circular water supply part. The circular water part is inserted into the foundation and a perpendicular flow is maintained. The tensiometer which measures pore pressure was installed at a depth of 50 mm in the centre of the water supply part. In order to obtain a constant pressure with the water supply part, the difference in the hydraulic head was set to 100 mm using the Marriott tank.

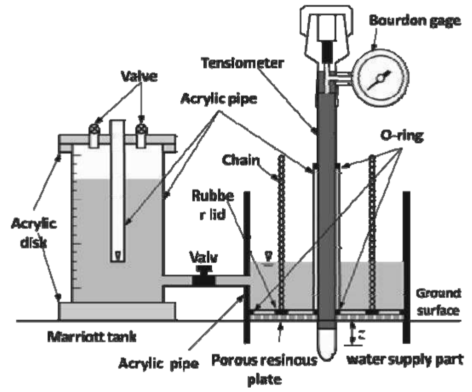

Figure 4. Experimental apparatus used for permeation test.

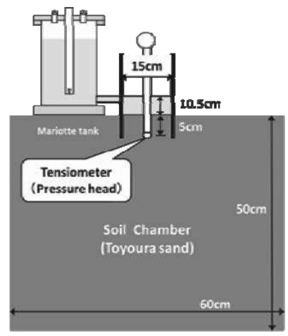

Figure 5. Setting for apparatus for permeation test.

3.2 *Calculation of saturated hydraulic conductivity*

Dry Toyoura sand was used for the permeation experiment, the results of which are shown in Fig. 6. When the pressure head becomes fixed at a depth of 50 mm, it turns out that the amount of infiltration is also fixed. When an observed pressure head maintained the same, it is judged that the point of 50mm in depth was saturated. Moreover, a hydraulic gradient can be estimated by subtracting the difference between the pressure head of the earth surface under the he circular water part, and the pressure head observed in the ground. The saturated coefficient of permeability became 1.0E-4 m/s when the incline of the accumulation amount of infiltration became a constant.

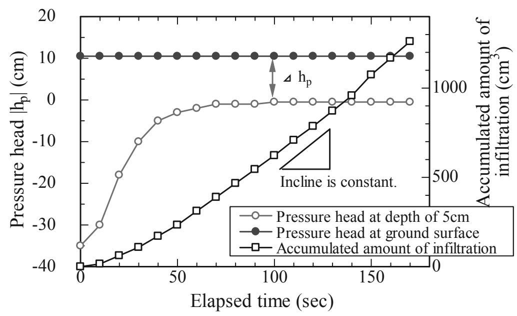

Figure 6. Measure values for permeation test

4 ESTIMATED MOISTURE DISTRIBUTION

4.1 *Linear approximation of the soil water distribution*

In order to calculate the hydraulic conductivity of unsaturated ground, information on the degree of saturation is required. In particular, in conditions of unsteady flow, since the amount of moisture changes with depth, it is necessary to accurately determine the distribution of moisture over time.

The authors therefore assumed a moisture distribution changes over time using the relation between Fig. 1 and Eq. 1. It is assumed that any infiltration assumes a trapezoidal distribution consisting of two components; the depth of the saturation front from ground surface and the depth of the wetting front. The saturation front in t hours can be calculated from Eq. 1. The wetting front can be determined by assuming by that it is equal to the trapezoidal area and the accumulation amount of infiltration. It is considered that the saturation front was 50 mm because the pressure head will be 0 mm at the tensiometer installed to a depth of 50 mm. The regression parameter of Eq. 1 can be estimated as follows:

$$H_f = \frac{8Q}{(\theta_s - \theta_r)\pi D^2} - H_s \tag{2}$$

where are, A is the trapezoid area, is volumetric water content of saturated soil and . *Q* is the amount of infiltration, and *D* is the radius of cylinder.

4.2 *Presumption of the moisture distribution using dynamic state soil moisture distribution model*

We performed a separate numerical simulation to verify whether the moisture distribution had a trapezoid distribution. The result is shown in Fig. 7. In comparison with numerical experimental results the inclines of the soil moisture distribution that was approximated with a trapezoid increase and become estranged. Moreover, the depth of the wetting front differed from the result obtained in the numerical analysis.

On the other hand, the trapezoid distribution accords with the numerical experimental result at the depth of the mean soil moisture. The authors therefore selected the dynamic state moisture distribution model to model moisture distribution (Eq.3 and Fig. 8). In this model, parameter a, which indicates the depth of the average moisture, and parameter b, which

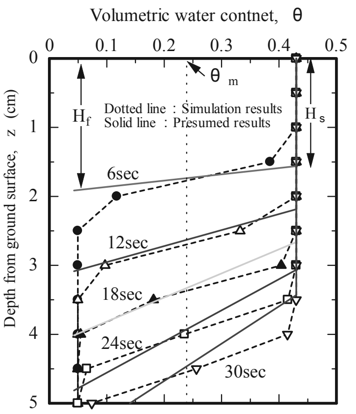

Figure 7. Inspection of the trapezoid distribution and water distribution by the numerical value experiment.

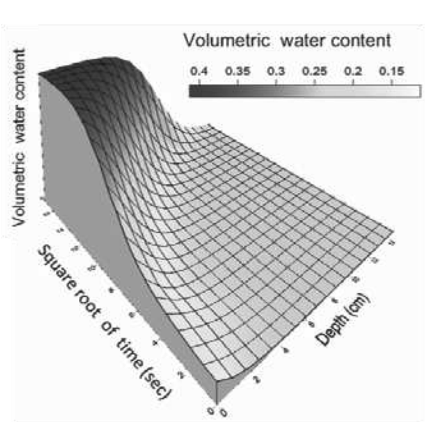

Figure 8. Dynamic state soil moisture distribution model

indicates the slope of the moisture distribution, are required. Since the average moisture can be inferred based on the initial moisture θ_i, is ($(\theta_s - \theta_i)/2 + \theta_i$), the conditions of exp(0) =1 are acquired. Therefore, if the depth zm is used as the average moisture, then Eq.4 can be derived as follows:

$$\theta = \frac{\theta_s - \theta_i}{1 + \exp(a + bz_m)} + \theta_i \tag{3}$$

$$a + bz_m = 0 \tag{4}$$

$$\frac{\partial \theta}{\partial z} = -\frac{(\theta_s - \theta_i) b \exp(a + bz)}{\{1 + \exp(a + bz)\}^2} \tag{5}$$

$$\left.\frac{\partial \theta}{\partial z}\right|_{z_m} = -\frac{(\theta_s - \theta_i) b}{4} \tag{6}$$

where, *a* and *b* are parameters of the dynamical moisture distribution model. Furthermore, the slope of the moisture distribution differentiates an Eq.3 with respect to *z*, which can be used to obtain Eq.5. Since Eq.5 is equivalent to the slope (Eq.6) of the moisture distribution expressed using the depth of a saturation front and *a* wetting front, parameter *b* can be obtained.

Parameter *a* can be obtained using Eq.4 and the parameters of an Eq.3 are identified. The result of the experimental and numerical moisture distributions is shown in Fig. 9. The dashed line shows the moisture distribution of the numerical

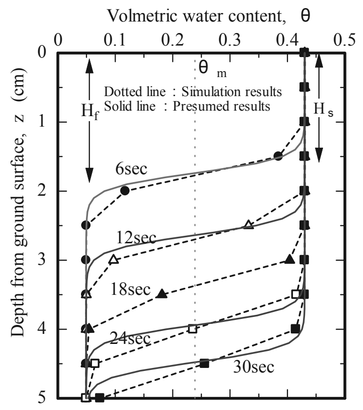

Figure 9. Water distribution inferred numerically and using the proposed method.

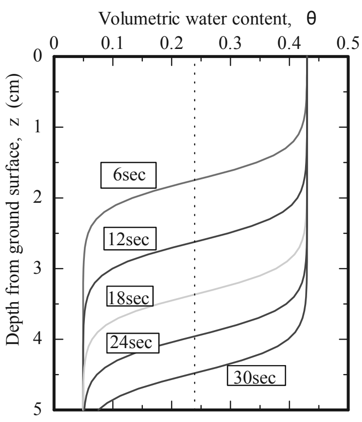

Figure 10. Presumed soil moisture distribution using the dynamic state soil moisture distribution model.

experimental result, the solid line the estimated moisture distribution from Eq.3. Fig. 9 shows that both are in agreement. The experimental result in the permeation test (Fig.4) obtained using the dynamic state moisture distribution model is shown in Fig. 10.

5 MOISTURE DISTRIBUTION IN RESPONSE TO HYDRAULIC PROPERTIES

5.1 *Moisture characteristic curve*

Fig. 11 shows the relationship between the water volume presumed from the pressure head and moisture distribution model for a depth of 50 mm, which is installing the tensiometer. Moreover, what showed the relation of the moisture characteristic from these is shown in Fig. 11. The moisture characteristic curve obtained in the laboratory experiments for reference is also shown in Fig. 12. Compared to the laboratory experiments, the absolute value of the pressure head was low. In order to carry out load of the water pressure of 100 mm to a permeation surface with the start of test, the air below a

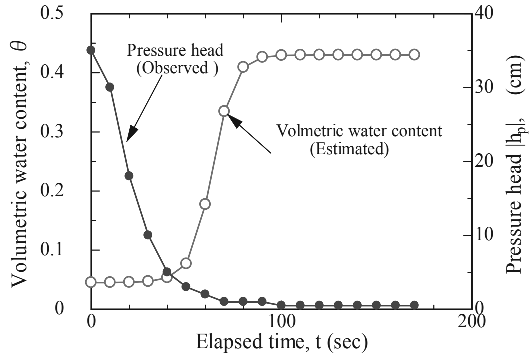

Figure 11. Presumed data from experimental results.

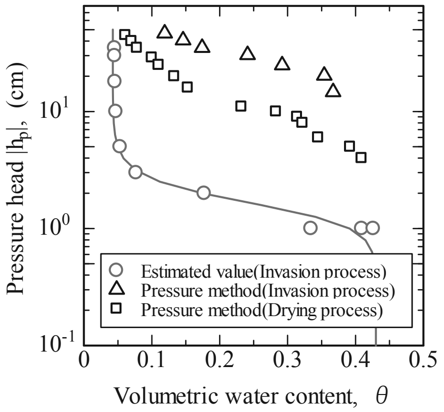

Figure 12. Data inferred from experimental results.

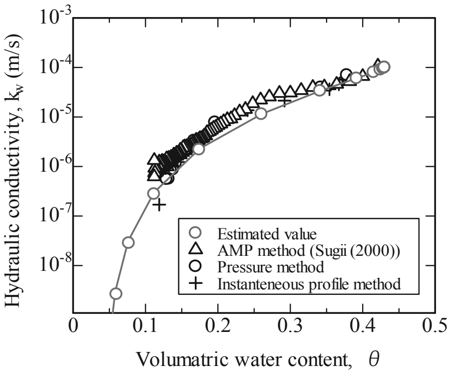

Figure 13. Presumed hydraulic conductivity of unsaturated soil.

permeation surface is confined. Therefore, it is considered that the pore air pressure became higher than the atmospheric pressure. Finally, it is measured lower than actual pore water pressure.

5.2 *Assumption of unsaturated hydraulic conductivity*

The parameters of the van Genuchten model can be estimated by our moisture characteristic curve of Fig. 12. The unsaturated hydraulic conductivity obtained using the Mualem model and the estimated parameters is shown in Fig. 13. The result of the proposed method was in agreement with other laboratory experimental results. By using the van Genuchten and Mualem models, since parameter n of the moisture characteristic curve is used, as shown in an Eq.7, it is considered that the slope of the moisture characteristic curve was evaluated correctly.

$$k_{unsat} = k_{sat} \cdot S_e^{0.5} \left\{ 1 - \left(1 - S_e^{n/(n-1)} \right)^{1-1/n} \right\}^n \qquad (7)$$

where, $S_e = (\theta_s - \theta)/(\theta_s - \theta_r)$, k_{unsat} is the hydraulic conductivity of unsaturated soil, k_{sat} is the hydraulic conductivity of saturated soil, and n is the parameter of the Genuchten and Mualem model.

6 CONCLUSIONS

The experimental results of the permeation tests and dynamic state soil moisture distribution model, the following conclusions could be drawn:

1) When there is no volume change, not only the wetting front but the depth of the saturation front is proportional to the square root of time.
2) The measurement values obtained for the amount of infiltration by permeation and the pore pressure of one point, can be used to calculate the parameters of a dynamic state moisture distribution model.
3) Hydraulic properties of the unsaturated foundation could be evaluated using the observed value of the presumed moisture distribution and pore pressure.
4) The pressure head of the moisture characteristic curve was affected by gap air and shifted to positive pressure; this needs to be improved in the future.

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