研 究 速 報

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Field Estimation of Hydraulic Conductivity in Uniform Anisotropic Soils

均質異方土壌における透水性の現地評価

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1. Introduction

Estimation of hydraulic conductivity in the field is often required in civil engineering practice, such as in dam and canal construction, and recharge facility design. Borehole test, also referred to as augur hole method, is the only geophysical method available for such measurement at arbitrary depths above the ground water level. In this test, a borehole is made in the ground to the depth where the soil conductivity is to be estimated and the infiltration rate from the borehole at constant water head is measured. The infiltration rate reduces with time until a steady infiltration rate is observed. This final infiltration rate is then used to estimate the soil conductivity based on various formulae. In a detailed analysis of the evaluation methodology, Stephan et al (1982) reported that all of the classical formulae available for this estimation to be inaccurate as they neglect the unsaturated and saturated flow mechanism that govern the flow from such tests. Therefore, in the absence of a reliable analytical solution, numerical models which solve the governing Richards' equation directly can be used to estimate the hydraulic conductivity in the field from the test results (Musiake and Herath, 1988).

In the analysis of the borehole test, in general the soil is assumed to be isotropic and uniform. This assumption does not hold valid for stratified soil formations where the vertical hydraulic conductivity can be very different to that in the horizontal direction. Specially in the design of infiltration trenches and wells, isotropic assumptions can lead to significant errors when the soil is actually anisotropic. This paper discusses a method of estimating hydraulic conductivity in anisotropic soils from two head borehole test using a steady state numerical model of the Richards' equation.

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2. Formulation of the Problem

The flow from the borehole test can be represented by the Richards equation given as,

$$\nabla \cdot [k(\varphi)\nabla(\varphi+z)]=c(\varphi)\frac{\partial\varphi}{\partial t} \quad (1)$$

The numerical solution of this equation takes a large amount of computer time due to the non-linear parameters which require small time steps in the unsteady state simulation. In the borehole test, required information is only that related to the final infiltration as this rate is the one measured in the field. Therefor, steady sate form of Richards' equation can be used to simulate the field test conditions. By representing the soil conductivity in the form of,

$$k(\varphi)=Ko\ kr(\varphi) \quad (2)$$

Where Ko is the saturated hydraulic conductivity and kr is the relative conductivity, it is possible to write the steady state of eq. (1) in radial coordinates,

$$O=\frac{1\partial}{r\partial r}\left[\gamma kr(\varphi)r\frac{\partial\varphi}{\partial r}\right]+\frac{\partial}{\partial z}\left[kr(\varphi)\frac{\partial}{\partial z}(\varphi-z)\right] \quad (3)$$

Where γ=kho/kvo (kho and kvo are the saturated conductivities in horizontal and vertical directions possible to estimate the infiltration rate from the borehole using Darcy's equation applied to the borehole boundary,

$$\frac{q}{K_{ov}}=\int_{\Gamma} k_r \nabla (\varphi+z) \qquad (4)$$

where q is the infiltration rate.

From the equations it can be seen that if the soil relative conductivity (kr(φ)) and the anisotropy ratio (γ) is known, it is possible to estimate the soil saturated conductivities Kvo and Kho using eq (3) and eq (4) together with the final infiltration rate observed (q). The kr (φ) can be taken as unique to a given soil. It can be either measured from soil samples or more easily generated from the (θ−φ) relation for the soil. To estimate both of the remaining parameters Kvo and γ, it is necessary to perform two borehole tests, at differnt water heads in the same borehole.

3. Estimating Soil Conductivity in Anisotropic Soils

The following method is proposed to estimate the soil conductivity in anisotropic soils using the bore hole test. First using the kr (φ) relation for the soil and the numerical model for eq (3), a set of q/Kvo curves are prepared for different values of γ, for a particular borehole diameter for different water heads.

In this paper average moisture suction relations of Kanto Loam soils shown in Fig. 1 and 2 are used for the study. These curves have been developed to represent the Kanto Loam soils using the soil properties of more than 100 sample measurements of shallow soil samples. For the ease of numerical simulation, the data are represented by the following equations. The moisture-suction relation (Fig. 1) by the equation,

$$\theta=\frac{\alpha(\theta_o-\theta_r)}{\alpha+[\ln(\varphi)]^{\beta}}+\theta_r$$

where θ=moisture content, and φ=suction in cm. The parameters for the relation in the figure are, $\alpha=72.8$, $\beta=3.92$, $\theta_o=0.707$, $\theta_r=0.598$.

The conductivity-suction relation (Fig. 2) is represented by the equation,

$$\mathrm{kr}(\varphi)=\frac{\alpha}{\alpha+\varphi^{\beta}}$$

with parameters $\alpha=131$ and $\beta=2.31$, for the curve shown in the figure.

The q/Kvo for different γ and water heads for the above soil properties are shown in Fig. 3. A 2-D numerical model for eq (3) using finite difference method was used for the simulation. All the results presented here are for a standard 22 cm diameter borehole. In the figure each curve represent q/Kvo values for one water head, with x axis representing Log of γ and y axis representing Log (q/Kvo). If the soil anisotropy is not known, for a given water head several combinations of vertical and horizontal saturated conductivities can give the same infiltration rate. These combinations of conductivities are represented by each curve for a particular water head.

If the soil formation can be assumed to be uniform, using two field tests conducted at two different water heads, common anisotropy value can be estimated from the two q/Kvo vs. γ curves of the test. This can be easily done as using a chart in the form shown in Fig. 4. Here one of the tests is taken as the standard

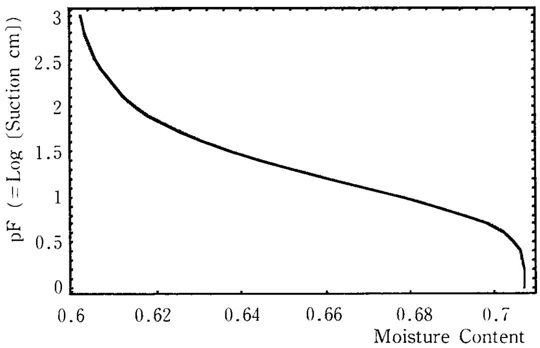

Fig. 1　Moisture-Suciton relation for Kanto Loam

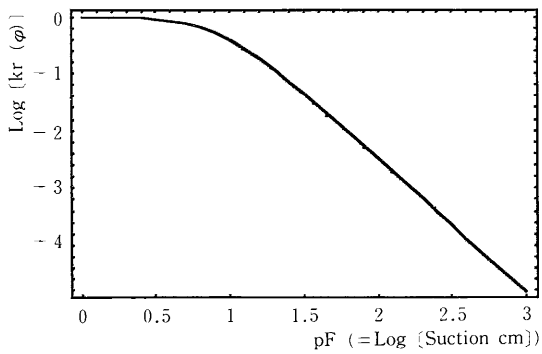

Fig. 2　Relative conductivity-Suction relation for Kanto Loam

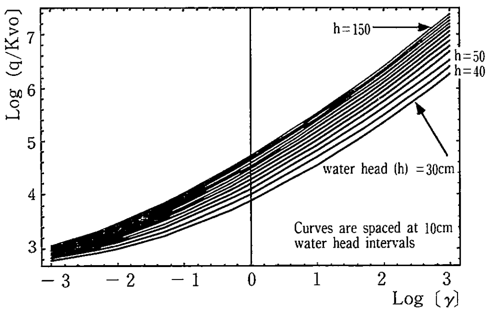

Fig. 3 Effect of anisotropy on the borehole discharge. Each curve represent the discharge for a single water head for 22cm diameter borehole in Kanto Loam

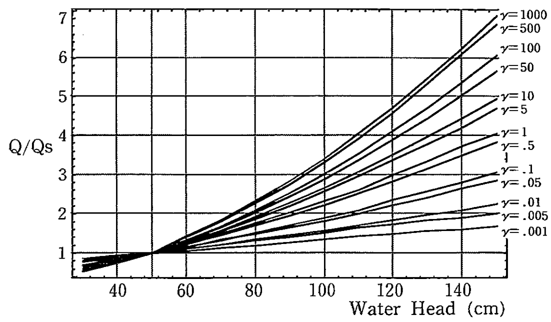

Fig. 4 Q/Qs (h=50cm, d=22cm) curves for borehole test in Kanto Loam

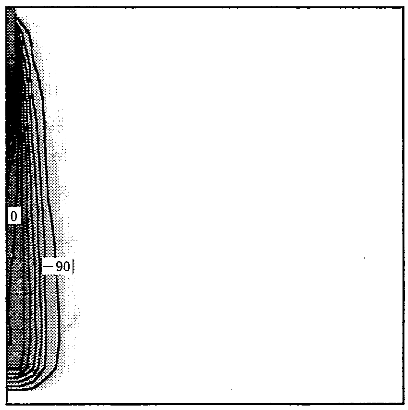

Fig. 5(a) Suction Distribution at final infiltration from borelole with g=1, γ=0.01cm, d=22cm for Kanto Loam

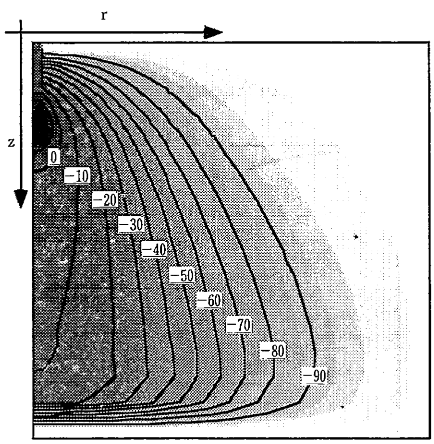

Fig. 5(b) Suction Distribution at final infiltration from borehole with γ=1, h=50cm, d=22cm for Kanto Loam

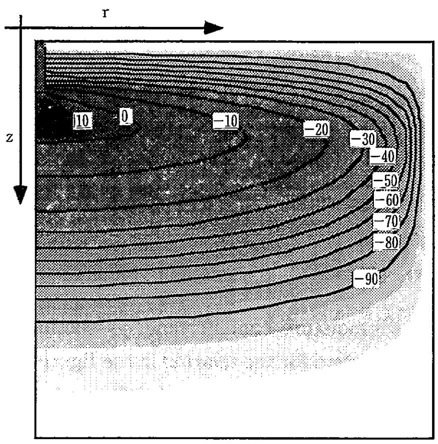

Fig. 5(c) Suction Distribution at infiltration from borehole with γ=100, h=50cm, d=22cm for Kanto Loam (assumed to be 50 cm head test) and the y axis is q/qs. Once the anisotropy (γ) is estimated, numerical simulation using the model for eq (3) is used to estimate the correct q/Kvo value, or it can be approximately estimated from the curves in Fig. 3. From the resulting q/Kvo value Kvo and hence Kho ($=\gamma$ Kvo) can be estimated.

The effect of anisotropy on the flow distribution can be clearly seen through the numerical simulation. Fig. 5 (a) to 5 (c) show the pressure profiles at steady state imposed by constant head boundaries. The pressure profiles are for $\gamma=0.01$, 1 and 100 for 50 cm water head in a 22 cm diameter borehole test. The important profile for the computations is the location of the stationary saturated bulb indicated by the 0 pressure line.

4. Example of a Field Application

Borehole tests were conducted in Nagayama catchment lying near to Tokyo metropolitan area, consisting of a Kanto Loam top soil layer. Two tests conducted at 50cm head and 100cm head for 22cm diameter borehole resulted in infiltration rates $q_{50}=39.93$ cc/s and $q_{100}=73.61$ cc/s. From these values $q_{100}/q_{50}=1.84$ and from Fig. 4, $\gamma\sim0.07$. Using this value saturated conductivities in horizontal and vartical directions are estimated as,

$$Kvo=1.4 \times 10^{-2} \text{ cm/s and } Kho=0.98 \times 10^{-3} \text{ cm/s}$$

These values closely agree with a separate analysis made using unsteady state parameter optimizing technique on the 50cm head test (Musiake & Herath 1988) which resulted in the values of Kvo$=1.14 \times 10^{-2}$ cm/s and Kho$=1.03 \times 10^{-3}$ cm/s.

5. Concluding Remarks

As seen in Fig. 3 there can be several combinations of vertical and horizontal saturated conducivities which would produce an observed infiltration rate from the borehole test. As the soil anisotropy becomes important in situations where infiltration from buried finite sources has to be predicted accurately, it is necessary to conduct borehole tests on at least two water heads.

As the curves similar to those in Fig. 4 can represent one class of soils, it is easy to prepare a set of such curves for the soils of interest for a given field simulation. Steady state simulation is computationally efficient and a set of curves similar to Fig. 4 can be prepared using a PC class machine in about 2-3 hrs. of computational time. However, it should be noted that the method is valid only for uniform soils, and not applicable to stratified formations.

Filed tests conducted around Tokyo area show that the estimation of soil saturated conductivity in the field is feasible using the above outlined procedure. Also the tests have shown that water heads used in the borehole should be at above 30cm to avoid air entrapment problems.

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