Determination of Hydraulic Conductivity of Sand Sediment Soil Taking an Inclusion of Gravel and Cobbles into Account

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ABSTRACT: The procedure to estimate the hydraulic conductivity of the sand sediment that is characterized by an inclusion of large gravel particles and cobbles in it was proposed. Assuming the descriptive cylindrical soil model representing sand, gravel/cobbles and void structures and applying the continuity law of water movement to the soil model, the functional relationship between the hydraulic conductivity of the sand sediment soil to be evaluated, the hydraulic conductivity of the sand soil measured by the laboratory or field permeability test, and the mass content of the gravel and cobbles in the soil was derived. The accuracy of the functional relationship mentioned above was examined by the series of the one-dimensional permeability test. A good comparison between the measurements and the estimation by the functional relationship was obtained. A numerical example was given to show the practical influence of the mass content of the gravel/cobbles on the prediction of the storm runoff in the sand sediment soil.

Key words: Sand sediment soil, Hydraulic conductivity of soil, Mass content of gravel and cobbles, Laboratory permeability test, Numerical calculation

INTRODUCTION

Hydraulic conductivity of soil plays an important role in predicting water movement in soil such as slope, irrigation field, and river embankment. The hydraulic conductivity of soil is usually determined by a laboratory permeability test or a field permeability test. When sand sediment soil is tested, some problem arises because the soil is characterized by an inclusion of large gravel particles and cobbles in it, and because a value that can be measured is only the hydraulic conductivity of the sand which is merely a part of the sand sediment soil. To solve the problem, the hydraulic conductivity of the sand sediment soil should be estimated from the value measured by the laboratory or field permeability test which is conducted on the sand soil. This is required because both the sand soil and the gravel/cobbles are integrated as a continuum porous material in usual predictions of water movement in soil by analytical methods or numerical methods.

In the present study, an integrated procedure to estimate the hydraulic permeability of the sand sediment soil from the laboratory or field permeability test is proposed. Firstly a descriptive cylindrical soil model representing sand, gravel/cobbles and void structures within the soil is assumed and a continuity law of water movement through it is introduced to derive a functional relationship between the hydraulic conductivity of the sand sediment soil to be evaluated, the hydraulic conductivity of the sand soil measured by the laboratory or field permeability test, and the mass content of gravel and cobbles in soil. Then the functional relationship proposed above is examined by the laboratory permeability test. Secondary a numerical example is given to show an effectiveness of the proposed functional relationship. Lastly some remarkable conclusions are given.

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HYDRAULIC CONDUCTIVITY OF SAND SEDIMENT SOIL

Theoretical derivation of hydraulic conductivity of sand sediment

In the analytical or numerical prediction of water movement through the sand sediment soil, both the sand and the gravel/cobbles are integrated into the continuum porous material, and the value of the hydraulic conductivity of the integrated porous material is required. But the value that can be measured is only the hydraulic conductivity of the sand soil which is merely a part of the sand sediment soil. Thus some procedure to estimate the hydraulic conductivity of the integrated sand-gravel/cobbles mass, K_i, from the measurement of the hydraulic conductivity of the sand, K_m, should be required. Here subscripts i and m mean the integrated value and the measured value of the hydraulic conductivity, respectively.

To propose the procedure mentioned above, the descriptive cylindrical soil model representing sand, gravel/cobbles and void structures is assumed as shown in **Figure 1**. A cross-sectional area A of the cylindrical soil model consists of the area of sand A_s, void A_v and gravel/cobbles A_g. It is well understood that the value of the hydraulic conductivity which is measured by the laboratory or field test represents the permeability of the region A_s+A_v. Denoting A_s+A_v by A_m and knowing that the hydraulic conductivity of A_m is described by K_m, then the water discharge through A_m is given by $q_m=(K_m \cdot i) \cdot A_m$ according to the Darcy law, in which i is a hydraulic gradient applied to the cylindrical soil model to move water along the axis as shown in **Figure 1**. q_m should equal the water discharge through A, that is $K_i \cdot A \cdot i$, in the numerical calculation of water movement because the gravel/cobbles are completely impervious. Thus K_i is written by:

$$K_i = \frac{q_m}{A \cdot i} = K_m \left(1 - \frac{A_g}{A} \right) \qquad 1$$

Assuming the same specific gravity G both for the sand and the gravel/cobbles, a dry density of the sand, ρ_d, which are measured by a soil sampling or a RI method is given by $G \cdot \rho_w \cdot A_s/A_m$, where ρ_w is a water density. And introducing a gravel content P that is defined as a ratio of mass of gravel/cobbles to sand plus gravel/cobbles, that is $A_g/(A_s+A_g)$, then **Equation 1** can be rewritten as:

$$\frac{K_i}{K_m} = 1 - \frac{1}{1 + \left(\frac{1-P}{P} \right) \left(\frac{G \cdot \rho_w}{\rho_d} \right)} \qquad 2$$

Equation 2 gives K_i, that is the hydraulic conductivity of the sand sediment soil, estimated from the known or measured values of K_m, P, G, ρ_d and ρ_w.

Laboratory permeability test

To examine an accuracy of **Equation 2**, a series of laboratory one-dimensional permeability test shown in **Figure 2** was conducted. The sand 1 mm in maximum particle diameter without fine soil particles was mixed by P with river gravel sieved into 10 to 15 mm in diameter, and compacted into an acrylic cylindrical column 10 cm diameter and 100 cm long. $P=10$, 20, 40 and 60% were selected successively in the series of the laboratory test. A flow discharge through the sand-gravel specimen was measured at the top outlet of the column to calculate the hydraulic conductivity of the sand-gravel specimen, K_i. The hydraulic gradient applied to the specimen was found from a regression line of total heads of water measured along the column as shown in **Figure 2**. The value of K_m was determined from the sand specimen without any gravel, that is $P=0\%$.

The test results are summarized in **Table 1**. Two tests were conducted for each P. The mass of the soil compacted into the column was divided by the specimen volume and modified by the water content

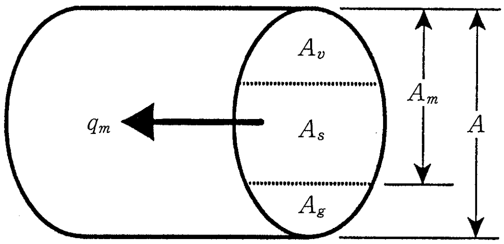

Figure 1 Descriptive cylindrical soil model representing sand, gravel/cobbles and voids.

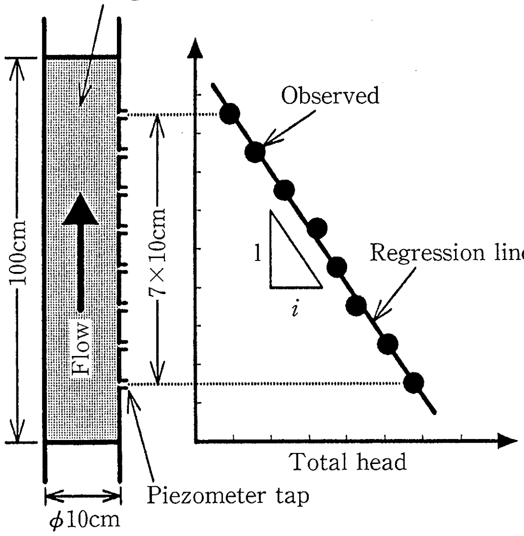

Figure 2 Schematic diagram of one-dimensional permeability test.

Table 1 Result of the one-dimensional permeability tests.

Mass content of gravel/cobbles P, %	Dry density of sand ρ_d, g/cm³	Hydraulic conductivity of sand-gravel specimen[b] K_i and K_m, cm/s
0[a]	1.47	5.78×10^{-3}
10	1.52	5.37×10^{-3}
	1.39	5.51×10^{-3}
20	1.54	5.02×10^{-3}
	1.45	5.12×10^{-3}
40	1.53	4.05×10^{-3}
	1.47	4.20×10^{-3}
60	1.44	2.86×10^{-3}
	1.41	3.03×10^{-3}

a) $P=0\%$ means the sand specimen without any gravel.
b) The value of $P=0\%$ corresponds to K_i, and others to K_m.

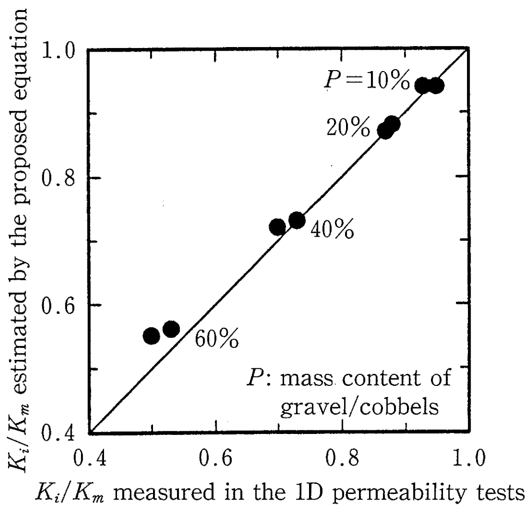

Figure 3 Comparison of the hydraulic conductivity between one-dimensional permeability tests and estimation by Equation 2.

of the soil to determine the dry density of the sand. **Figure 3** shows a comparison of K_i/K_m measured in the laboratory tests with the estimation by **Equation 2** with $G=2.65$. A fairly good comparison of K_i/K_m between the estimations and the measurements shows a practical accuracy of **Equation 2**. K_i/K_m estimated by **Equation 2** is some larger than the measurement at $P=60$ %. This may be due to a non-uniform, but unavoidable, distribution of the gravel particles within the specimen formed during pouring the sand-gravel mixture into the cylindrical column.

NUMERICAL EXAMPLE

As shown in **Equation 2**, P is a key parameter that determines the soil permeability of the sand sediment. To show a practical influence of P on the prediction of the water movement in soil, a numerical sand sediment soil suffering from a heavy storm as shown in **Figure 4** is selected and analyzed by the saturated-unsaturated flow FEM [1]. The numerical sand sediment soil 100 m long and 20 m thick suffers from the storm 30 mm/hr during 24 hours along its top surface and slope. $K_m=3.0\times10^{-2}$cm/s, $G=2.65$, and $\rho_d=1.35$g/cm^3 are employed based on the field permeability tests and investigations[2] to calculate K_i by **Equation 2**. The unsaturated moisture properties of the soil were described by the van GENUCHTEN's functional relationships[3] determined by the field permeability test[4] using a Guelph pressure infitrometer[5]. An initial degree of saturation was assumed to be 60% in the numerical sand sediment soil.

Figure 5 gives the numerical calculations of the cumulative outflow through the soil slope from beginning to end of the storm. 0, 20, 40 and 60% of P were compared in the numerical calculations, in which $P=0$% means a case of the sand soil without the gravel/cobbles. It is found in **Figure 5** that, if the value of the hydraulic conductivity of the sand soil measured by the laboratory or field permeability test is directly employed in the numerical prediction of the flow in the sand sediment soil, the amount of the flow through the soil will be overestimated and, inversely, the flow over the soil surface underestimated.

CONCLUSIONS

The procedure to estimate the hydraulic conductivity of the sand sediment that is characterized by an inclusion of large gravel particles and cobbles in it was proposed. Assuming the descriptive cylindrical soil

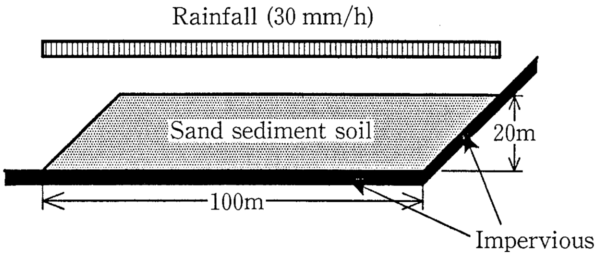

Figure 4 Numerical sand sediment soil to examine the effect of P on runoff prediction.

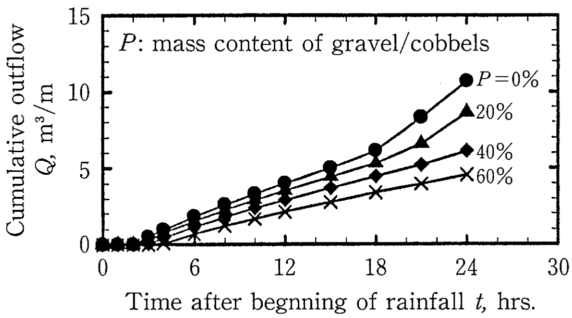

Figure 5 Cumulative outflow from the numerical sand sediment soil with time calculated by the FEM.

model representing sand, gravel/cobbles and void structures and applying the continuity law of water movement to the soil model, the functional relationship between the hydraulic conductivity of the sand sediment soil to be evaluated, the hydraulic conductivity of the sand soil measured by the laboratory or field permeability test, and the mass content of the gravel and cobbles in the soil was derived. The accuracy of the functional relationship mentioned above was examined by the series of the one-dimensional permeability test. A good comparison between the measurements and the estimation by the functional relationship was obtained. A numerical example was given to show the practical influence of the mass content of the gravel/cobbles on the prediction of the storm runoff in the sand sediment soil.

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礫と巨石の混入を考慮した土砂堆積地盤の透水係数の推定

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摘　　要

礫と巨石が混入する土砂堆積地盤の透水係数の推定方法を提案した。まず、土砂堆積地盤を構成する砂、礫・巨石および間隙を模式的に表した円筒状の土要素モデルを想定し、流れの連続条件を適用した。これにより、土砂堆積地盤全体の透水係数、室内あるいは現場透水試験で測定される砂の透水係数、ならびに土中に占める礫・巨石の質量含有率の関係を記述する理論式を誘導した。次に、この理論式の精度を、室内一次元透水試験により調べた。試験結果と理論式から推定した値の間に良好な一致が得られた。最後に、土砂堆積地盤における豪雨流出問題を対象に、流出量の推定結果に与える礫・巨石含有率の影響を示した。

キーワード：土砂堆積地盤、土の透水係数、礫・巨石の質量含有率、室内透水試験、数値計算

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