Practical Determination of Hydraulic Conductivity of Sand Sediment Soils

Toshihiro Morii [1], Yuji Takeshita [2] and Mitsuhiro Inoue [3]

Abstract: An integrated procedure to determine hydraulic conductivity of sand sediment soil that is characterized by an inclusion of gravel particles and cobbles in sand soil is proposed. Firstly the Guelph pressure infiltrometer (GPI) method to measure the soil permeability of the sand is introduced and extended so that it can estimate unsaturated moisture properties of the soil. Secondly a descriptive cylindrical soil model representing sand, gravel and cobbles, and voids within soil is assumed to determine the hydraulic conductivity of the sand sediment soil. A continuity law of flow discharge through the cylindrical soil model is introduced to derive theoretically a functional relationship of the hydraulic conductivity of the sand sediment soil with the hydraulic conductivity of the sand measured by the GPI method and the gravel content of the soil. An accuracy of the functional relationship of the hydraulic conductivity is examined by laboratory permeability test. Finally the GPI method and the functional relationship of the hydraulic conductivity are integrated to determine the soil permeability of the sand sediment soil. A numerical example is given to show an effect of the gravel content of soil on a storm runoff over the sand sediment soil.

Keywords: *Sand sediment soil*; *Hydraulic conductivity of soil*; *Guelph pressure infiltrometer*; *Gravel content by mass*

1 Introduction

Permeability of sand sediment soil distributed in a valley watershed is a key parameter that may trigger a mountainous disaster such as a debris flow and a storm runoff over the soil. It is usually difficult to determine accurately and practically hydraulic conductivity of the sand sediment soil by using in-situ permeability test or laboratory permeability test of soil. This is because a value which can be measured by the in-situ or laboratory permeability test is only the hydraulic conductivity of sand which is merely a part of the sand sediment soil, and because the hydraulic conductivity of the sand sediment soil can be never characterized by this value of the sand permeability. This complicated and practically important problem restricts our accurate prediction of a water movement within the sand sediment soil or a flood runoff over the soil by using a numerical procedure based on a continuum theory.

In this study an integrated procedure to determine the hydraulic conductivity of the sand sediment soil that is characterized by an inclusion of large gravel particles and cobbles in the sand soil is proposed. In the integrated procedure, the hydraulic conductivity of the sand soil is measured by using an in-situ permeability test, and then an overall hydraulic conductivity of the sand sediment soil (in Section 3.1 this hydraulic conductivity is denoted by $K_{unified}$) is estimated by taking account of a continuity of water flow through soil and a gravel content in soil. A Guelph pressure infiltrometer (GPI) method, which was developed by Reynolds and Elrick (1990) and Elrick and Reynolds (1992), is employed to measure the hydraulic conductivity of the sand soil. The GPI method is classified into a constant-head infiltration method and provides a simple in-situ permeability test. A field-saturated hydraulic conductivity of soil, K_{fs}, is determined by measuring a constant-head infiltration into soil from a single ring inserted into the soil surface in the GPI method.

In the following, firstly, a test procedure of the GPI method is outlined and extended so that the GPI method can determine unsaturated moisture properties of soil. Moisture content beneath the soil surface around the GPI ring is measured with time, and a genetic algorithm combined with a numerical saturated-unsaturated flow analysis is employed to estimate parameters describing the unsaturated moisture properties of soil from the infiltration rate and the moisture content measured with time during the GPI test. Secondly a functional relationship is theoretically derived to evaluate the hydraulic conductivity of the sand sediment soil. A descriptive cylindrical soil model representing sand, gravel and cobbles, and voids within the soil is assumed and a continuity law of flow discharge through it is introduced to derive the functional relationship of the hydraulic conductivity of the sand sediment soil with the hydraulic conductivity of sand measured by the GPI method and the gravel content of the soil. The functional relationship which gives the hydraulic conductivity of the sand sediment soil is examined by a series of laboratory permeability test. Finally the integrated procedure that consists of the GPI method and the functional relationship of the hydraulic conductivity derived above is proposed to evaluate the soil permeability of the sand sediment. A numerical example is given to show a practical influence of the gravel content of soil on a storm runoff in the sand sediment soil. Some concluding remarks follow it.

2 In-situ permeability test using GPI

2.1 GPI method

The GPI consists of a single steel ring with a radius a inserted into the soil to depth d, a water supply tube and a water reservoir as shown in Figure 1 (Morii *et al.*, 2000). The position of an air tube keeps the constant head of water H applied on the soil surface within the ring. Only the infiltration rate Q_s measured after the infiltration from the single ring into the soil reaches a quasi-steady state is required in the GPI method. Then the value of K_{fs} is calculated by the following equation

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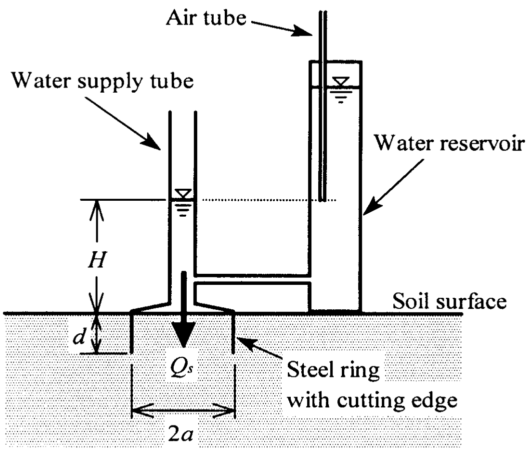

Figure 1: Schematic diagram of the GPI apparatus

(Reynolds and Elrick, 1990; Elrick and Reynolds, 1992):

$$K_{fs} = \frac{\alpha^* G Q_s}{\alpha^* a H + a + \alpha^* \pi a^2 G} \quad (1)$$

where G is a dimensionless shape factor which takes account of the geometry of the infiltration surface within the ring. G is given by

$$G = 0.316\frac{d}{a} + 0.184 \quad (2)$$

In (1), α^* is a power describing an exponential relationship of unsaturated hydraulic conductivity with negative pressure head of soil, and is interpreted as an index of texture/structure component of soil capillarity. The GPI method requires that α^* be site-estimated by simple observation of soil. Values of α^* for various soil textures and structures are recommended by Elrick and Reynolds (1992).

2.2 In-situ permeability test

A practical effectiveness of the GPI method was examined by an in-situ permeability test conducted in the sand sediment soil about 50 m wide, 160 m long and 10 m thick. The sand sediment soil tested had been formed in the narrow valley of the mountainous watershed by the debris flow of soil. Five test points 10 to 20 m apart each were selected in the sand sediment soil. The soil contains a large number of gravel particles 30 to 70 cm in diameter and the sand to gravelly sand deposited among the gravel and cobbles as shown in Figure 2. The in-situ permeability tests using the GPI method were conducted on the surface soil at five test points. After completion of the tests, the soil was excavated about 1 m in depth by a back hoe and man-hands, and then the in-situ permeability tests using the GPI method were again carried out on the surface of the excavated soil. The steel ring with a= 5.5 cm was inserted about d= 3.0 cm into the soil, and 15 to 17 cm of H were applied on the soil surface in the tests. Figure 3 shows the results of grain size analysis of the sand. The soil near the sediment surface and the soil deposited in the deeper portion of the sediment are classified into sand and gravelly sand, respectively. In the GPI method, α^*= 0.12 cm^{-1} was adopted based on the site observation of the sand.

Figure 2: Sand sediment soil including gravel and cobbles

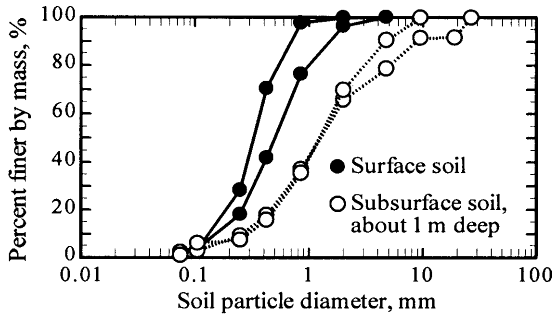

Figure 3: Grain size distribution of the sand tested

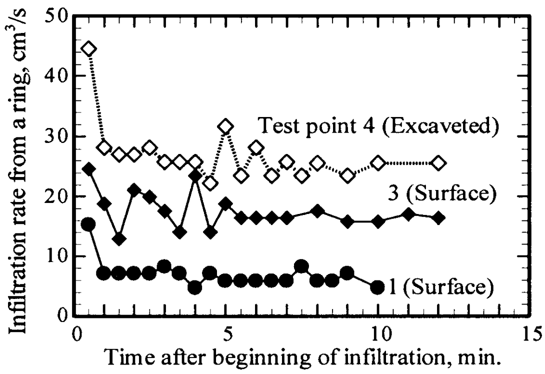

Figure 4: Typical examples of the infiltration rate measured during the in-situ permeability test using the GPI

Typical examples of the infiltration rate measured during the in-situ permeability test using the GPI method are shown in Figure 4. As the soil tested is sand to gravelly sand, only 5 to 10 minutes were required to measure Q_s irrespective of the preceding moisture condition of the soil. The total time required for setting the GPI apparatus, supplying water into the water reservoir and measuring the infiltration rate was a half to one hour.

K_{fs} of the soil determined by (1) and corrected at 15 degree centigrade of water temperature are summarized in Table 1. Two measurements were repeated with slightly changing H at each test point. The in-situ tests on the excavated soil at Test point 2 were conducted in failure because of interference due to the small stone during the steel ring insertion into the soil. Sixteen values of K_{fs} given in Table 1 excluding those of Test point 2 are analyzed statistically to find out whether the values of K_{fs} are significantly different in the soil surface plane as well as along the soil depth. Table 2 shows the result of an analysis of variance based on a two-way layout method. Two factors describing the test point on the soil surface (that is Test point #1 to #5 on the soil surface and on the excavated soil surface) and the soil depth (that is the soil surface and the excavated soil surface) are selected, and both a variance ratio and a level of significance of these factors are calculated in the analysis of variance. It is found that the sand sediment soil is homogeneous in terms of permeability in plane area as the probability of significance is not so small. But difference in K_{fs} measured at the surface soil and the excavated soil is statistically highly significant. From the result shown in Table 2, the sand sediment soil tested has non-uniform property of permeability along depth into the soil. This may be well explained by a process of sedimentation of sand and large gravel contained in the debris flow, where more massive gravel settles faster than smaller sand particles. This also can be explained by comparing the grading curves given in Figure 3. It may be right to conclude that a simplicity and rapidness of measurement provided by the GPI method realizes the statistical analysis of the soil permeability which has scarcely been tried in a soil investigation. This should be one of special features of the GPI method.

Table 1: K_{fs} of the sand soil [a] determined by the GPI method.

Soil depth	Surface		Excavated [c]	
Repeat [b]	#1	#2	#1	#2
Test point 1	1.06×10^{-2}	1.48×10^{-2}	8.16×10^{-2}	8.32×10^{-2}
Test point 2	4.01×10^{-2}	5.96×10^{-2}	-	-
Test point 3	4.05×10^{-2}	2.96×10^{-2}	1.86×10^{-1}	5.58×10^{-2}
Test point 4	1.65×10^{-2}	3.04×10^{-2}	4.85×10^{-2}	4.15×10^{-2}
Test point 5	2.66×10^{-2}	3.40×10^{-2}	4.13×10^{-2}	5.99×10^{-2}

a) K_{fs} (cm/s) are corrected at 15 degrees in centigrade of water temperature.
b) Two measurements were repeated with slightly changing H at each test point.
c) Tests on the excavated soil at Test point 2 were conducted in failure.

Table 2: Result of the analysis of covariance to examine statistical property of soil permeability

Factors [a]	Degree of freedom	Variance ratio F_o	Level of significance p [b]
Test point (A)	3	1.36	0.323
Soil depth (B)	1	8.76	0.018 **
A×B	3	1.01	0.437
Error	8	-	-
Sum	15	-	-

a) A×B shows an interaction of the factors A and B on K_{fs}.
b) A set of two asterisks means that the factor has statistically a highly significant effect on K_{fs}.

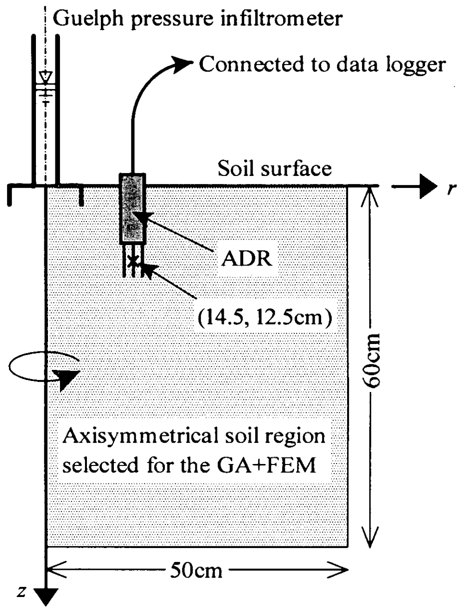

Figure 5: ADR inserted near the GPI ring to measure volumetric moisture content during infiltration

2.3 Estimation of unsaturated moisture properties of soil

The GPI method was extended so that it could estimate the unsaturated moisture properties of soil. Figure 5 outlines the extension of the GPI method, where a volumetric moisture content beneath the soil surface near the GPI ring is measured by using a moisture sensor, Theta Probe type ML2x (Delta-Devices Ltd.), during the constant-head infiltration from the ring. Both the infiltration rate and the volumetric moisture content measured with time during the GPI test were simulated iteratively by using the genetic algorithm (GA) combined with a FEM saturated-unsaturated flow analysis (GA+FEM) to estimate the unsaturated moisture properties of the soil (Takeshita and Morii, 2002). Functional relationships among volumetric moisture content, negative pressure head and unsaturated hydraulic conductivity of soil were assumed to be described by van Genuchten's equation (van Genuchten, 1980). The most optimal set of values of the soil parameters describing the functional relationships were determined by the GA so that it minimized a sum of squared deviations between the measurement and the FEM calculation of both the infiltration rate and the volumetric moisture content.

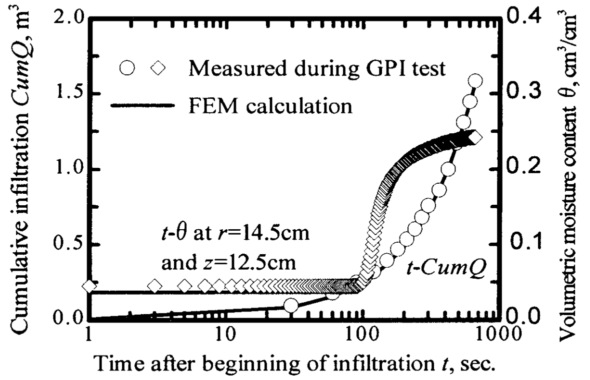

Figure 6: Comparison of cumulative infiltration and volumetric moisture content between the measurement and the FEM calculation after the GA+FEM iterations

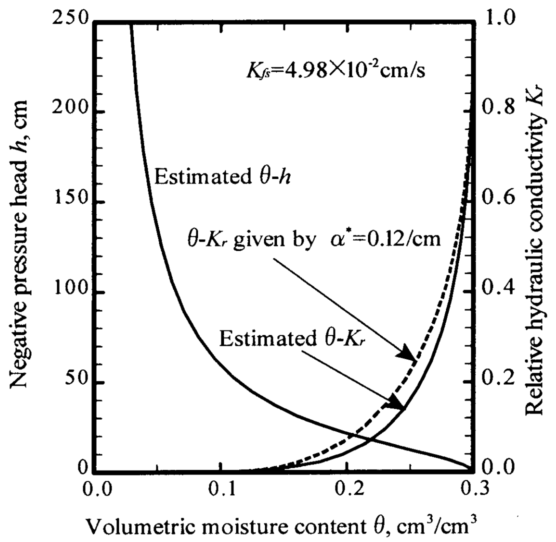

Figure 7: Unsaturated moisture properties of the sand estimated by the GA+FEM

An axisymmetric soil region, 50 cm in radius and 60 cm in depth, was selected for the FEM calculation as shown in Figure 5.

The measured data at Test point 3 shown in Table 1 were analyzed by the GA+FEM. Figure 6 shows comparison of the cumulative infiltration and the volumetric moisture content between the measurement and the FEM calculation which was obtained after the iterative estimations by the GA+FEM. Using the most optimal set of the soil parameters estimated in Figure 6, the van Genuchten's functional relationships of the unsaturated moisture properties of the sand are determined as shown in Figure 7. A relative hydraulic conductivity along the right y-axis of Figure 7 is defined as a ratio of the unsaturated hydraulic conductivity of soil to K_{fs}. A dotted line in Figure 7 is an exponential relationship of the unsaturated hydraulic conductivity of the sand that is drawn by using the recommended value of α^* mentioned in Section 2.1. A fairly good agreement of the unsaturated hydraulic conductivity between the van Genuchten's functional relationship and the dotted exponential line may mean that the introduction of the GA+FEM analysis into the in-situ GPI test provides practical estimation of the unsaturated moisture properties of soil.

3 Hydraulic conductivity of sand sediment soil

3.1 Hydraulic conductivity of sand sediment soil derived from cylindrical soil model

In the numerical prediction of flow through the sand sediment soil as shown in Figure 2, both the sand and the gravel are totally unified into a porous continuum mass, and the value of the hydraulic conductivity of this unified porous mass is required. But the value that can be measured by the in-situ or laboratory permeability test is only the hydraulic conductivity of the sand which is merely a part of the sand sediment soil. Thus some procedure to evaluate the hydraulic conductivity of the unified mass of the sand and the gravel, $K_{unified}$, from the measurement of K_{fs} of the sand is needed.

To solve the problem mentioned above, a descriptive cylindrical soil model representing sand, gravel and voids is assumed as shown in Figure 8. A cross-sectional area A of the cylindrical soil model consists of the area of sand, void and gravel denoted by A_s, A_v and A_g, respectively. It is well understood that the value of the hydraulic conductivity which is measured by the in-situ permeability test represents the permeability of the region A_s+A_v. Denoting A_s+A_v by A_m and the hydraulic conductivity of A_m by K_m, then the flow discharge through A_m is given by $q_m=(K_m \cdot i) \cdot A_m$ in which i is a hydraulic gradient applied to the cylindrical soil model to move water along the axis as shown by a thick arrow in Figure 8. An amount of q_m should be equal to the flow discharge through A, that is $K_{unified} \cdot A \cdot i$, in the numerical calculation of flow because the gravel are completely impervious. Thus the hydraulic conductivity of the unified mass A is given by

$$K_{unified} = \frac{q_m}{A \cdot i} = K_m\left(1 - \frac{A_g}{A}\right) \quad (3)$$

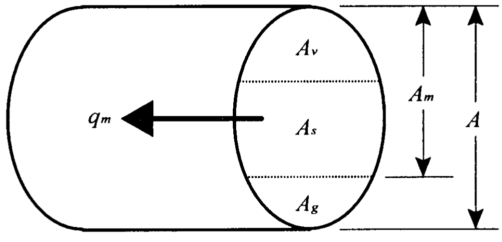

Figure 8: Descriptive cylindrical soil model assumed to derive the hydraulic conductivity of the sand sediment soil, $K_{unified}$

Assuming the same specific gravity G both for the sand and the gravel, and introducing a gravel content P that is defined as a ratio of mass of gravel to that of sand plus gravel, $A_g/(A_s+A_g)$, then (3) can be rewritten as

$$\frac{K_{unified}}{K_m}=1-\frac{1}{1+\left(\frac{1-P}{P}\right)\left(\frac{G\cdot\rho_w}{\rho_d}\right)} \qquad (4)$$

where ρ_d is a dry density of the sand and ρ_w is a water density. It should be noted that K_m in (4) corresponds to K_{fs}.

To examine an accuracy of (4), a series of laboratory one-dimensional permeability tests was conducted. Sand, 1 mm in maximum particle diameter and without fine 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 in diameter and 100 cm long. P= 10, 20, 40 and 60 % were selected successively in the series of the laboratory one-dimensional permeability tests. A flow discharge through the soil specimen was measured at the top outlet of the column to determine the hydraulic conductivity of the sand mixed with the gravel, that is $K_{unified}$. The hydraulic gradient applied to the soil specimen was found from the measurement of total head along the soil column. The value of K_m was determined from the sand specimen without any gravel (P= 0 %).

Figure 9 shows a comparison of $K_{unified}/K_m$ measured in the laboratory one-dimensional test with the estimation by (4) with a known value of G= 2.65. Two specimens were prepared in each test of P. A fairly good agreement of $K_{unified}/K_m$ between the measurement and the estimation shows a practical accuracy of (4). $K_{unified}/K_m$ estimated by (4) is slightly larger than the measurement at P= 60 %. This may be due to a non-uniform distribution of the gravel particles within the specimen, formed during pouring the sand-gravel mixture into the cylindrical column.

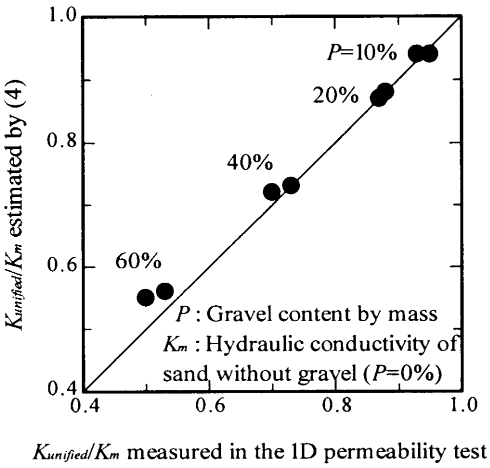

Figure 9: Comparison of the hydraulic conductivity of the sand-gravel mixture between the estimation by (4) and the laboratory permeability test

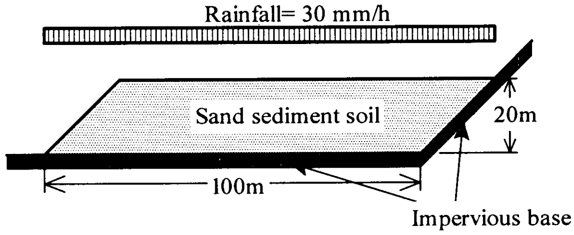

Figure 10: Numerical sand sediment soil to show practical influence of the gravel content on a prediction of storm runoff

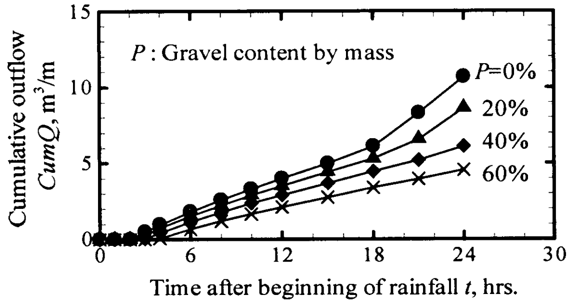

Figure 11: Cumulative outflow from the numerical sand sediment soil with time calculated by the FEM in which $K_{unified}$ estimated by (4) is employed

3.2 Numerical example of storm runoff on sand sediment soil

As shown in (4), P is a key parameter that characterizes the permeability of the sand sediment soil. To show a practical influence of P on a prediction of storm runoff, a numerical sand sediment soil as shown in Figure 10 is selected and analyzed by the saturated-unsaturated flow FEM (Morii, 1999). The numerical sand sediment soil 100 m long and 10 m thick suffers from the storm 30 mm/h during 24 hours along its top surface and slope. K_{fs}= K_m= 3.0×10^{-2} cm/s, G= 2.65, and ρ_d= 1.35 g/cm^3 were given according to some results of the in-situ test in Section 2.2 to calculate $K_{unified}$ by (4). The unsaturated moisture properties of the soil were described by the van Genuchten's functional relationships estimated in Section 2.3 and given in Figure 7. An initial degree of saturation in the numerical sand sediment soil was assumed to be 60 %.

Figure 11 shows the numerical calculations of cumulative outflow through the soil slope from beginning to end of the storm. P= 0, 20, 40 and 60% were compared in the numerical calculations, in which P= 0% represents the sand soil without any gravel. It is found in Figure 11 that, if the value of the hydraulic conductivity of the sand measured by the in-situ permeability test is directly used 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 is underestimated.

4 Conclusions

The integrated procedure to determine the hydraulic conductivity of the sand sediment soil that is characterized by an inclusion of the large gravel particles and cobbles in the sand was proposed. Firstly the Guelph pressure infiltrometer method was employed to measure the field-hydraulic conductivity of the sand, and extended so that it can determine the unsaturated moisture properties of the soil. Secondly the descriptive cylindrical soil model representing sand, gravel and voids was assumed to derive the functional relationship of the hydraulic conductivity of the sand sediment soil with the hydraulic conductivity of the sand measured by the GPI and the gravel content of the soil. The functional relationship derived was successfully examined by the laboratory permeability test. Finally a numerical example was given to show the practical influence of the gravel content on the prediction of storm runoff in the sand sediment soil.

The following is remarked:

a) The GPI method was effectively applied to the sand sediment soil to determine the field-saturated hydraulic conductivity of soil. It was found that the procedure to determine the field-saturated hydraulic conductivity of soil is consistently and is not time-consuming. It may be practically important to show that the permeability of soil could be statistically evaluated owing to simplicity and rapidness of measurement of the GPI method.
b) The GPI was extended to measure the volumetric moisture content near soil surface during the constant-head infiltration. Both the infiltration rate and the volumetric moisture content measured with time were successfully analyzed by the GA+FEM to estimate the soil parameters that describe the unsaturated moisture properties of soil.
c) The hydraulic conductivity of the unified soil mass, which represents the permeability of the sand sediment soil, was theoretically derived by applying the continuity law of flow to the descriptive cylindrical soil model, and effectively examined by the laboratory permeability test. The key parameter that characterizes the hydraulic conductivity of the sand sediment soil is the gravel content by mass. The numerical prediction of the storm runoff in the sand sediment soil showed the practical influence of the gravel content.

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