

Development of In Situ Permeability Test Using Constant Discharge Method for Sandy Soils

A. Rifa'i, Y. Takeshita, M. Komatsu

Abstract—The post-rain puddles problem that occurs in the first yard of Prambanan Temple are often disturbing visitor activity. A poodle layer and a drainage system had ever built to avoid such a problem, but puddles still did not stop appearing after rain. Permeability parameter needs to be determined by using a simpler procedure to find exact method of solution. The instrument modelling was proposed according to the development of field permeability testing instrument. This experiment used a proposed Constant Discharge method. Constant Discharge method used a tube poured with constant water flow from unsaturated until saturated soil condition. Volumetric water content (θ) were monitored by soil moisture measurement device. The results were correlations between k and θ which were drawn by numerical approach from Van Genuchten model. Parameters θ , optimum value obtained from the test was at very dry soil. Coefficient of permeability with a density of 19.8 kN/m^3 for unsaturated conditions was in range of $3 \times 10^{-6} \text{ cm/sec}$ ($S_r=68\%$) until $9.98 \times 10^{-4} \text{ cm/sec}$ ($S_r=82\%$). The equipment and testing procedure developed in this research was quite effective, simple and easy to be implemented on determining field soil permeability coefficient value of sandy soil. Using constant discharge method in proposed permeability test, value of permeability coefficient under unsaturated condition can be obtained without establish soil water characteristic curve.

Keywords—Constant discharge method, in situ permeability test, sandy soil, unsaturated conditions.

I. INTRODUCTION

PRAMBANAN Temple is a 9th-century Hindu temple compound in Central Java, Indonesia. The temple compound, a UNESCO World Heritage Site, is the largest Hindu temple site in Indonesia and one of the biggest in the Southeast Asia. To preserve the heritage buildings and to enhance the convenience of tourist activities, restoration and facilities reparation around the temple are required.

Due to heavy equipment activities during restoration period after Yogyakarta earthquake in May, 2006, soil in temple yard has become dense and ponding area occurred during rainfall. Post-rain puddles which occurred at certain parts of Prambanan Temple yard is one of issues that needs to be solved. This condition shows that the existing drainage system is not sufficient.

Rainwater infiltration process above the ground surface can also be the cause of puddling. Infiltration is influenced by the characteristics of porous material or soil porosity. It initiates

the alteration of soil condition from unsaturated to saturated which causes the change of soil permeability coefficient.

This research is focused on development of more simple equipment for in situ testing to measure permeability under both saturated and unsaturated conditions. The determination of permeability coefficient value was initiated from unsaturated soil condition to saturated soil condition.

II. LITERATURE REVIEW

Reference [4] proposes an experiment to measure unsaturated hydraulic conductivity for sandy soil. Firstly, Guelph Pressure Infiltrometer (GPI) was used to determine the value of hydraulic conductivity in saturated conditions. Secondly, the unsaturated hydraulic conductivity was measured by Instantaneous Profile Method during drainage test. The values of volumetric water content were measured using a PR1 Profile Probe type (Delta-T Devices Ltd.) as an indicator of saturated soil condition.

Values of hydraulic conductivity in unsaturated condition were obtained from numerical models as [5]. The field permeability test was conducted for top soil in Piyungan waste disposal site in Yogyakarta, Indonesia. Fig. 1 shows the relationship between k and volumetric water content from unsaturated until saturated condition. This field experimental method can be a good practical in-situ permeability test because of its simple procedure. However, this method is only limited to the soil in disposal site with homogenous and uniform type of soil. In addition, the used tools were also considered too complex and difficult to obtain in Indonesia. Saturation indicator was only determined when the moisture sensor devices were used. Therefore, we need a tool that is simple, inexpensive, precise, and able to test the soil with a higher density.

III. METHOD

A. Testing Points

16 field testing points were selected and distributed within the area of first yard on Prambanan Temple as shown in Fig. 2.

B. Constant Head Permeameter Test

The obtained observation data from the test were substituted into Darcy equation:

$$k = \frac{QL}{hAt} \quad (1)$$

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where A is sample section and Q is water volume in measuring glass, h is the height difference of energy, t is flow time, and L is sample length or current length.

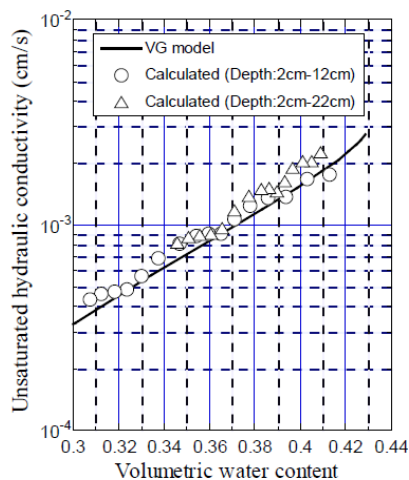


Fig. 1 Unsatrated hydraulic conductivity calculated by the IP method as [4]

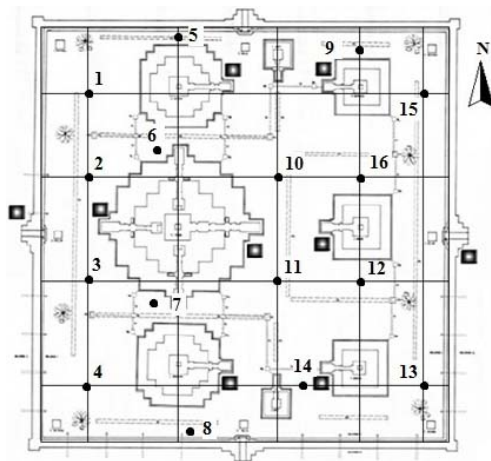


Fig. 2 Locations of testing points and sampling

C. Soil Moisture Device Instrument Calibration

The testing procedure was conducted according to guidance given by the manufacturer. The calibration test was conducted using oven-dried soil collected from first yard of Prambanan Temple.

D. Laboratory Soil Permeability Testing at Unsaturated Condition

This test was performed by creating a sample of Prambanan Temple soil in a container with certain density. Laboratory soil permeability testing at unsaturated condition was conducted using constant water reservoir and container and soil moisture sensor device instrument as the indicator of soil saturation in wetting and drying process through the change of volumetric water content values. Laboratory tests were performed through two process including wetting and drying.

E. Density Test

The aim of this test is to obtain the value of field soil density. Sand cone testing was performed for 16 testing points.

F. Permeability Test and Volumetric Water Content Measurement

This test aims to obtain the value of field permeability coefficient at ground surface by using permeability test instrument model and developed testing procedure at 16 testing points at the first yard of Prambanan Temple.

The measurement of volumetric water content was conducted by using soil moisture sensor devices instrument during the field permeability test procedure. The measuring process was initiated from unsaturated soil condition until soil had become saturated. In addition to the instrument model as [4], development and simplification of field permeability test instrument for sandy soil was also conducted. Referring to this result and laboratory constant-head permeability testing concept, the new instrument model, named Constant Discharge model, was created.

In testing procedure, using Constant Discharge model as illustrated in Fig. 3, casing borehole was installed by staking casing pipe to the soil with sampling depth of $1D$ from ground surface where D is casing diameter, then followed by the installation of permeameter pipe.

The height of sample was equal to sample diameter or $1D$ based on the preliminary test results. Soil moisture sensor was staked below casing. After both pipes and soil moisture sensor instrument were properly installed, data logger was connected to laptop and soil moisture sensor. Data interpretation were obtained using data logger device instrument to read and save volumetric water content data.

The test was performed by making an unsaturated soil conditions to be saturated, so that the water discharge through the sample would be equal to the initial discharge when entering permeameter pipe ($Q = \text{constant}$). Water was flowed using constant water reservoir and container which was continuously flowed by water with constant discharge through permeameter pipe. In this test, it was assumed that groundwater level was at the edge of sample casing. Initial volumetric water content (θ_i) was being recorded. At a certain time, with constant flow discharge Q , water level at permeameter pipe would become constant ($H = \text{constant}$), volumetric water content θ_2 was then obtained. This test was conducted by conditioning the soil from unsaturated to saturated condition. The permeability coefficients were calculated by (2):

$$k = \frac{Q}{FH} \quad (2)$$

with, k = coefficient of permeability of soil (cm/sec); Q = water discharge (cm³/sec); F = geometric factor (cm); H = height of water level inside the wells (cm). According to [3], (2) was used to calculate the permeability coefficient (k) at steady flow condition. Discharge used in the calculation used the discharge flow into the casing permeameter. It was

assumed that the water table was located at the end of the casing samples. Then for borehole conditions, the value of F (geometry factor) is according to [1], [3] calculated by (3):

$$F = \frac{\pi D}{1 + \frac{11L}{\pi D}} \quad (3)$$

with, R = radius of the wells (cm); L = thickness of existing soil in the well (cm).

The value of unsaturated coefficient of permeability (k_{unsat}) for any depth of soil can be calculated by (4) according to [2]:

$$k_{unsat} = \frac{\int_0^z \frac{\partial \theta}{\partial t} dz}{\left(\frac{\partial h}{\partial t} + 1 \right)} \quad (4)$$

where h is pressure head, t is time, z is depth, and θ is volumetric water content. Measurement of volumetric water content value was conducted by soil moisture probe until the water level was constant or no significant changes. Value of hydraulic gradient was assumed to 1.0 so it was not necessary to know the parameters of Soil Water Characteristic Curve which is quite expensive. Testing scheme is shown in Fig. 3. Values of permeability coefficient in unsaturated conditions were obtained from numerical models as [5] using equation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (ah)^n} \right]^m \quad (5)$$

$$k(S_e) = k_s S_e^{0.5} \left[1 - \left(1 - S_e^{1/m} \right)^n \right]^b \quad (6)$$

where, $m = 1-1/n$, S_e is effective degree of saturation, θ_s saturated volumetric water content, θ_r is residual volumetric water content, k_s is saturated permeability coefficient, α and n are empirical parameter. Equation (6) usually is named as VG model. Some unknown parameters were measured from Hydruss-2D data base for sandy soil.

G. Preliminary Test

The testing procedure plan considered the value of the geometry factor and the sample casing according to [1], [3]. Tests were conducted on sandy soil which was located in Department of Civil Engineering, Faculty of Engineering, Universitas Gadjah Mada.

Based on preliminary test results, the model and testing procedures could be used in the field to measure coefficient of permeability. The height of sample was equal to sample diameter or 1D based on the ease of installation of casing samples, the disturbance factor in soil samples, the testing duration, and the test results that had been relatively good. Preliminary test data are shown in Table I.

TABLE I
RESULTS OF PRELIMINARY TEST

No	Height of sample	Type of soil	k_{IF} (cm/s)	k_{CD} (cm/s)
1	0.5D	SW-SM	$1,97 \times 10^{-3}$	$1,13 \times 10^{-3}$
2	1.0D	SW-SM	$3,46 \times 10^{-3}$	$2,15 \times 10^{-3}$
3	1.5D	SW-SM	$3,51 \times 10^{-3}$	$2,38 \times 10^{-3}$
4	2.0D	SW-SM	$3,64 \times 10^{-3}$	$2,61 \times 10^{-3}$

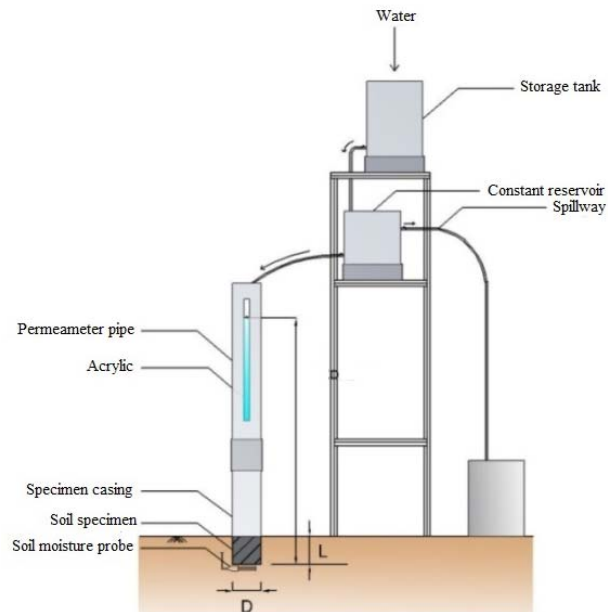


Fig. 3 Scheme of the permeability test instrument (Constant Discharge model)

IV. RESULTS AND DISCUSSION

A. Calibration of Soil Moisture Sensors Instrument

Calibration was conducted at the laboratory using soil from the first yard of Prambanan temple. The calibration results of soil moisture sensor device are shown in Fig. 4.

B. Soil Properties

Soil classification refers to Unified Soil Classification System (USCS). Grain size distribution testing was performed at 16 sample points taken from soil of the first yard of Prambanan temple.

The test result shows that there are two types of soil at the first yard Prambanan temple which are well graded sand-silty sand (SW-SM) and silty sand (SM). Specific gravity testing was conducted at both soil types and it was obtained that G_s of SW-SM soil was 2.66 while for SM soil was 2.60.

C. Laboratory Permeability Test for Unsaturated Condition

Laboratory permeability test in unsaturated condition was performed at SW-SM soil with density of 18.0 kN/m^3 and 19.8 kN/m^3 . The test result was correlation of volumetric water content (θ) starts from wetting to drying process and time function (t) for SW-SM soil as displayed in Fig. 5. Parameter θ_s is volumetric water content value in saturated condition and the value of θ_r need to be performed in trial for several

conditions. These trial conditions were when the soil was initially oven dried with the value of 4,5% and at the end of the test with the value of 17%.

Based on (4) and (6), the correlation between k and θ can be obtained. Based on Fig. 5 the coefficient of permeability can be determined. Fig. 6 shows the permeability coefficient with variation of volumetric water content for sandy soil using constant discharge method. The value of permeability coefficient for unsaturated conditions with a field density of 19.8 kN/m^3 was in range of $3 \times 10^{-6} \text{ cm/sec}$ ($S_r=68\%$) until $9.98 \times 10^{-4} \text{ cm/sec}$ ($S_r=82\%$).

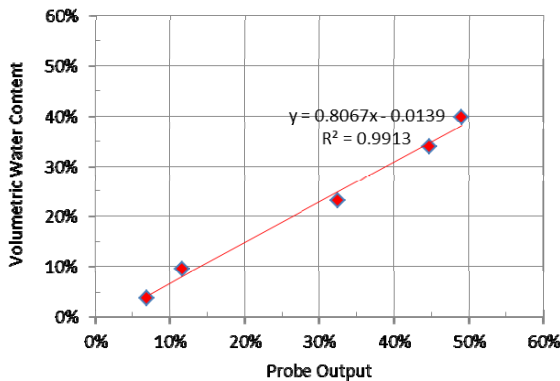


Fig. 4 Calibration of soil moisture sensor

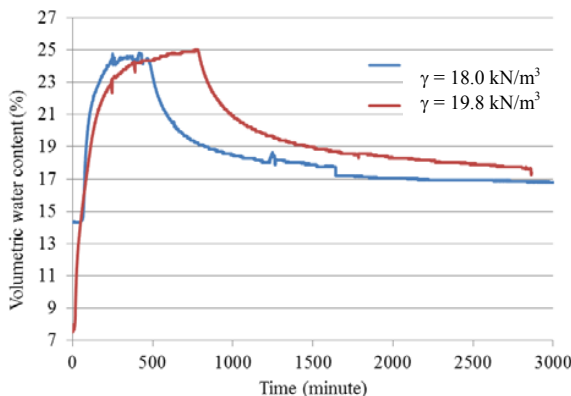


Fig. 5 Various volumetric water content value during permeability test

D. Field Unsaturated Coefficient of Permeability

Based on the value of volumetric water content changes during the testing procedure logged by soil moisture sensor instrument, the coefficient of permeability using constant discharge method for unsaturated conditions could be obtained. Parameters θ_r used in the calculation were obtained from the result of laboratory test. The field unsaturated coefficient of permeability of Prambanan temple yard with density of 19.8 kN/m^3 is shown in Fig. 7.

As shown in Fig. 5, it is found that the influence of various density was not significant to unsaturated soil. In the soil with different densities, the difference of saturated volumetric water content value and residual volumetric water content value is less significant.

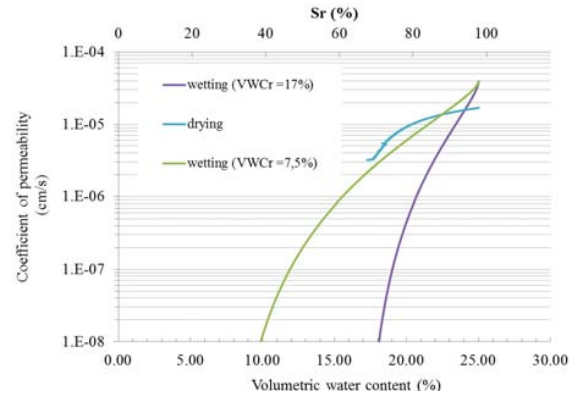


Fig. 6 Unsaturated coefficient of permeability for sandy soil using constant discharge method

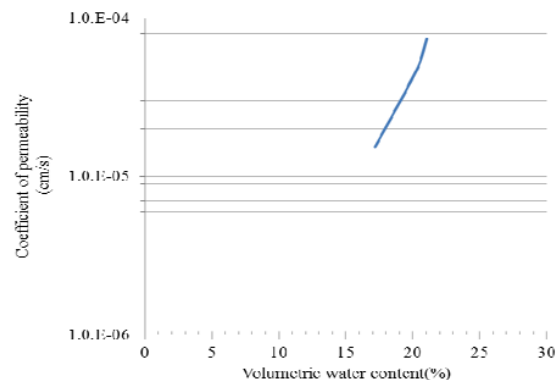


Fig. 7 Field unsaturated coefficient of permeability of Prambanan temple yard

From field testing result in unsaturated condition, the data show that soil permeability coefficient value in unsaturated condition is increasing along with the increment of volumetric water content due to less ability of soil to flow water during initial wetting. The amount of water, penetrated the soil during initial wetting, filled soil pore cavities which were previously filled with air so water could not pass through the soil.

The determination of permeability coefficient value using VG model is required some parameters which can be obtained through testing and modeling. The parameters are θ_s , θ_r , and n . In this research, comparison was made between the graphic of k vs θ and variation of θ_r value as shown in Fig. 6. It shows that the increasing value of θ_r resulted in more vertical curve and the decreasing value of θ_r resulted below the curve. The curve of wetting procedure is close to curve of drying with the value of $\theta_r = 7.5\%$ which is in very dry soil condition.

E. Effect of Soil Density on Coefficient Permeability

Soil density level was measured due to dry volume weight of the soil. Relationship between coefficient of permeability value and density is shown in Fig. 8. The result mainly shows the tendency of decreasing permeability value for increasing soil dense.

F. Comparison of Permeability Coefficient

The value of soil permeability coefficient in saturated condition were obtained using proposed constant discharge method and conventional constant head method as laboratory standard. Testing results are shown in Fig. 9. In general, the value of permeability coefficient which obtained from proposed constant discharge method is higher than constant head method. The difference in permeability coefficient values is maybe caused by the sample dimension. This research is still on primary stage. It needs a further study on effect of sample dimension.

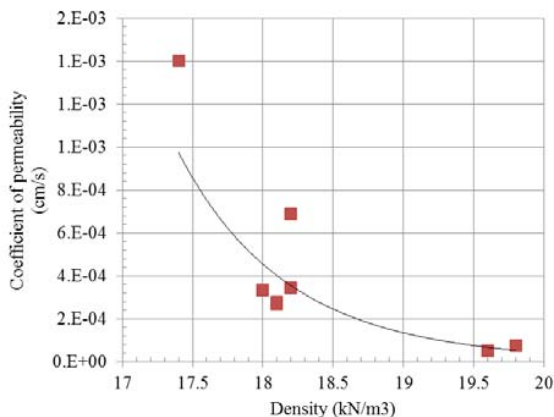


Fig. 8 Density influence against permeability

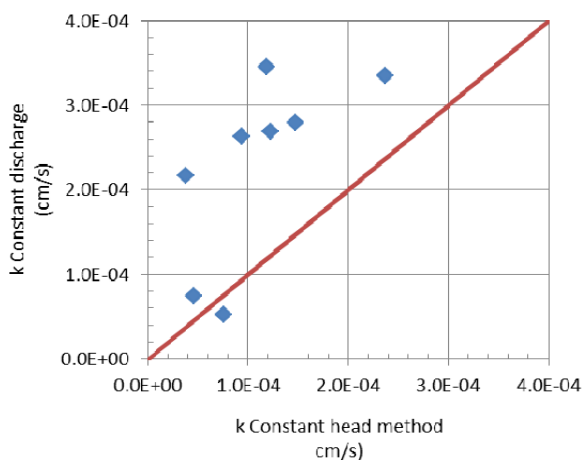


Fig. 9 Testing results in saturated condition

V. CONCLUSIONS

Development of more simple equipment and procedure for in situ testing to measure permeability under both saturated and unsaturated conditions were carried out. The equipment and testing procedure developed in this research were quite effective, simple, and easy to implement in obtaining field soil permeability coefficient value for sandy soil. The proposed constant discharge method can be used to determine soil

permeability coefficient from unsaturated to saturated condition without establishing soil water characteristic curve.

Soil layer at the first yard of Prambanan temple is grouped as well graded and sand-silty sand. Coefficient of permeability with field density of 19.8 kN/m^3 for unsaturated conditions was in range of $3 \times 10^{-6} \text{ cm/sec}$ ($S_r=68\%$) until $9.98 \times 10^{-4} \text{ cm/sec}$ ($S_r=82\%$) using proposed constant discharge method. The correlation between permeability coefficient and volumetric water content (θ) from unsaturated to saturated condition for sandy soil can be discovered.

In general, the value of permeability coefficient which obtained from proposed constant discharge method was higher than constant head method. The difference in permeability coefficient values was caused by the sample dimension. This research is still in early stage. It needs further study on the effect of sample dimension. Further research about the influence of sample casing and permeameter pipe diameter as well as various sample heights due to permeability coefficient is needed.

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