Determination of Unsaturated Soil Permeability Based on Geometric Factor Development of Constant Discharge Model

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

Abstract**—**After Yogyakarta earthquake in 2006, the main problem that occurred in the first yard of Prambanan Temple is ponding area that occurred after rainfall. Soil characterization needs to be determined by conducting several processes, especially permeability coefficient (*k*) in both saturated and unsaturated conditions to solve this problem. More accurate and efficient field testing procedure is required to obtain permeability data that present the field condition. One of the field permeability test equipment is Constant Discharge procedure to determine the permeability coefficient. Necessary adjustments of the Constant Discharge procedure are needed to be determined especially the value of geometric factor (*F*) to improve the corresponding value of permeability coefficient. The value of *k* will be correlated with the value of volumetric water content (θ) of an unsaturated condition until saturated condition. The principle procedure of Constant Discharge model provides a constant flow in permeameter tube that flows into the ground until the water level in the tube becomes constant. Constant water level in the tube is highly dependent on the tube dimension. Every tube dimension has a shape factor called the geometric factor that affects the result of the test. Geometric factor value is defined as the characteristic of shape and radius of the tube. This research has modified the geometric factor parameters by using empty material tube method so that the geometric factor will change. Saturation level is monitored by using soil moisture sensor. The field test results were compared with the results of laboratory tests to validate the results of the test. Field and laboratory test results of empty tube material method have an average difference of 3.33×10^{-4} cm/sec. The test results showed that modified geometric factor provides more accurate data. The improved methods of constant discharge procedure provide more relevant results.

Keywords**—**Constant discharge, geometric factor, permeability coefficient, unsaturated soils.

I. Introduction

PRAMBANAN Temple is one of the world's cultural heritages located in Indonesia that needs to be maintained and preserved. The first yard of Prambanan Temple is a location where there are three main temples at Prambanan Temple place. This location always occurs ponding area after rain. This ponding occurred ponding area disturbs the tourists' activity. Improvement of the drainage system is the solution of this problem. The appropriate drainage system to solve this problem is porous drainage system that can effectively reduce the ponding area. An important parameter to design the porous drainage system is soil permeability coefficient.

One of the innovations in the field of civil engineering especially in geotechnical aspects is the development of in situ permeability test. Mostly, soil permeability test was done in the laboratory with Falling Head Permeameter for clay and Constant Head Permeameter for sandy soil. Laboratory permeability test is not efficient considering the distance, time, and cost to make a sample test in the laboratory. Development of in situ permeability test can answer the limitations of the laboratory permeability testing. One procedure that is being developed is Constant Discharge Model [3]. Constant Discharge Model can perform soil permeability test in the field on unsaturated and saturated soil conditions. Based on [3], the testing procedure is different from laboratory testing. Constant Discharge test equipment still needs to be developed in order to produce more accurate test results. One of the necessary parameters that can improve the results is shape factor or geometric factor. A geometric factor used as one of the parameters in the test needs to be developed and improved. In this paper, Constant Discharge procedure will be improved with a different method of the previous testing. An improved method of work is expected to produce better results so it can support the planning of drainage on the first yard of Prambanan Temple.

II. Literature Review

Reference [3] performs a field permeability test for granular soil. The soil permeability test equipment is formed of pipes and metal casing that is plugged into the ground equipped with constant water reservoir and container. The soil permeability test equipment is combined with a soil moisture sensor for measuring the volumetric water content. This procedure is named Constant Discharge Model. The tests were performed by two processes. First is the wetting process and the second is drying process. The wetting process is done until soils are saturated and then drying process is started by flowing the water until the soil is dry. The testing scheme is shown in Fig. 1.

The testing procedure is flowing water into the tube with constant flow discharge. One of the decisive parameters to find out the value of permeability coefficient at unsaturated conditions is the value of volumetric water content. Value of field volumetric water content was measured by using soil moisture sensors combined with data logger devices. This

A. Rifa'i is with the Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Indonesia (phone: +62-274-545675; fax: +62-274-554809; e-mail: ahmad.rifai@ ugm.ac.id).

Y. Takeshita and M. Komatsu are with the Graduate School of Environmental and Life Science, Okayama University, Okayama, 700-8530, Japan (e-mail: yujitake@cc.okayama-u.ac.jp, mkomatsu@okayama-u.ac.jp).

testing procedure is performed to make the soil from unsaturated to be saturated conditions. This method is done after the ground reaches saturation at constant discharge test that can be seen during the reading of volumetric water content reaches constant conditions. Then, the water flow at constant discharge apparatus is switched off and there will be water seepage into the ground. Value volumetric water content measured during this process. The data will be used to calculate the value of permeability coefficient in unsaturated conditions.

In a testing procedure using Constant Discharge model as illustrated in Fig. 1, casing borehole was installed by staking casing pipe to the soil with a sampling depth of 1*D* from ground surface where *D* is casing diameter, then followed by the installation of permeameter pipe. The permeability coefficients were calculated by (1):

$$k = \frac{Q}{FH} \tag{1}$$

where, k = coefficient of permeability of soil (cm/sec); Q = water discharge (cm^3/sec); F = geometric factor (cm); H = height of water level inside the wells (cm).

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], [4] calculated by (2):

$$F = \frac{2\pi R}{1 + \frac{11L}{2\pi R}} \tag{2}$$

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

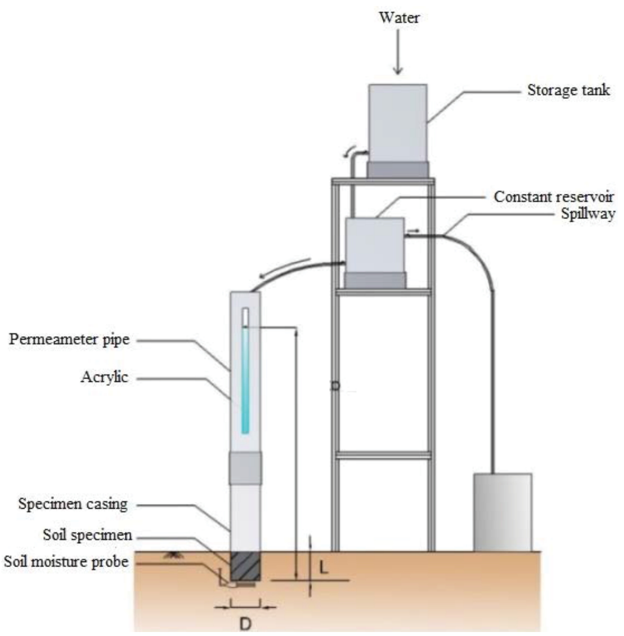

Fig. 1 Scheme of the permeability test instrument (*Constant Discharge model*) as [3]

III. Method

A. Preliminary Test

A preliminary test of research intended to determine a more precise method related to the use of a constant discharge permeability testing in the field. It is based on research conducted [3] which shows the difference between the value of a considerable field testing by the laboratory. So that needs to be revisited related variables that influence in determining the future value of permeability coefficient and permeability coefficient value in the field using a constant discharge can be more representative when compared to laboratory testing. The analysis was performed on the parameter of geometric factor (F). Based on [3], a geometric factor that was used is shown in (2). In the geometric factor, there is a constant number that will be analyzed. The constants number in the (2) will be approached so that the value of a field permeability coefficient is more representative to the laboratory. The results of the analysis are shown in Table I.

TABLE I
GEOMETRIC FACTOR APPROACH

Point	k_{field}	k_{lab}	F	$F_{corrected}$	n
1	1.40 x 10^{-3}	2.89 x 10^{-4}	6.002	29.12	-0.026
2	6.89 x 10^{-4}	1.18 x 10^{-4}	6.002	34.95	-0.083
3	3.45 x 10^{-4}	1.18 x 10^{-4}	6.002	17.44	0.020
4	3.35 x 10^{-4}	2.37 x 10^{-4}	6.002	8.46	0.801
5	4.55 x 10^{-5}	4.55 x 10^{-5}	6.002	9.92	0.629
6	2.27 x 10^{-3}	4.55 x 10^{-5}	6.002	299.45	-0.332
7	2.68 x 10^{-4}	1.22 x 10^{-4}	6.002	13.22	0.381
8	2.79 x 10^{-4}	1.47 x 10+	6.002	11.31	0.507
9	5.18 x 10^{-5}	7.53 x 10^{-5}	6.002	4.22	1.973

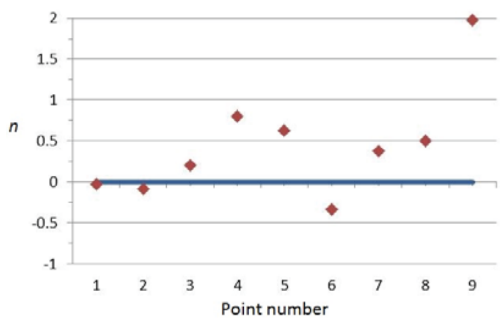

Fig. 2 Distribution of *n* value

Fig. 2 shows the distribution of constants number (n) is around zero. it was decided to replace the constant number 11 in (2) with 0. Therefore (2) turns into F = 2πR, this equation is equal to (3):

$$F = 2\pi R \tag{3}$$

Based on the results of data processing, it used two methods in a preliminary test. The first method of testing is done exactly the tests performed by [3] is the method of fill material tube with constant discharge procedure, using (2). The second method is a method of empty tubes in the same procedure, using (3). Sketches of the improved method are shown in Fig. 3.

B. Testing Points

Six field testing points were selected and distributed within the area of the first yard on Prambanan Temple as shown in Fig. 4.

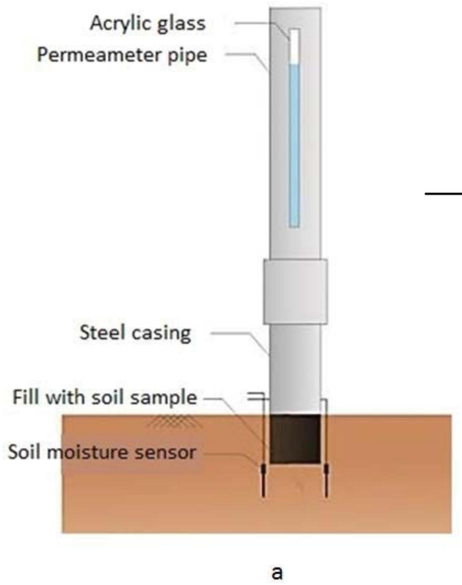

Fig. 3 Sketches of the improved method (a) fill material tube method and (b) empty material tube

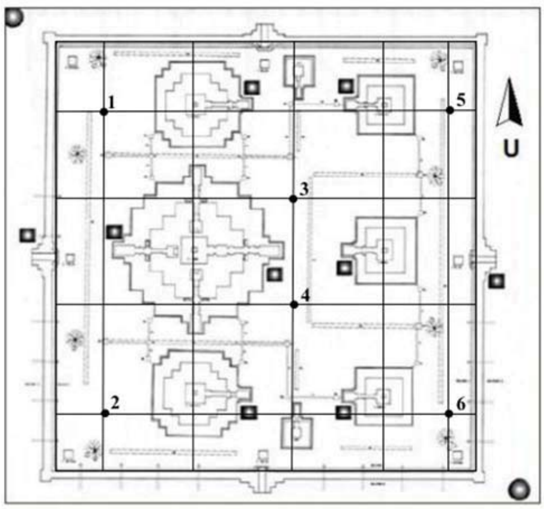

Fig. 4 Locations of testing points and sampling

C. Permeability Test

This test aims to obtain the value of field permeability coefficient by using permeability test instrument model and developed testing procedure. The testing procedure used is the constant discharge method development model with the improved geometric factor parameter.

Field test using constant discharge model was conducted by punching the holes in the surface soil by using a core cutter casing. The depth of the hole is equal to the diameter of the core cutter. Furthermore, the soil moisture sensor is mounted on the bottom of the casing. Then, the permeameter pipe is installed in the surface ground. Water poured through the casing permeameter with a constant flow. So that at a certain time after the test progresses, the water level is stable (H = fixed). Permeability coefficient is calculated by (1) and a geometric factor with (3). Testing scheme is shown in Fig. 5.

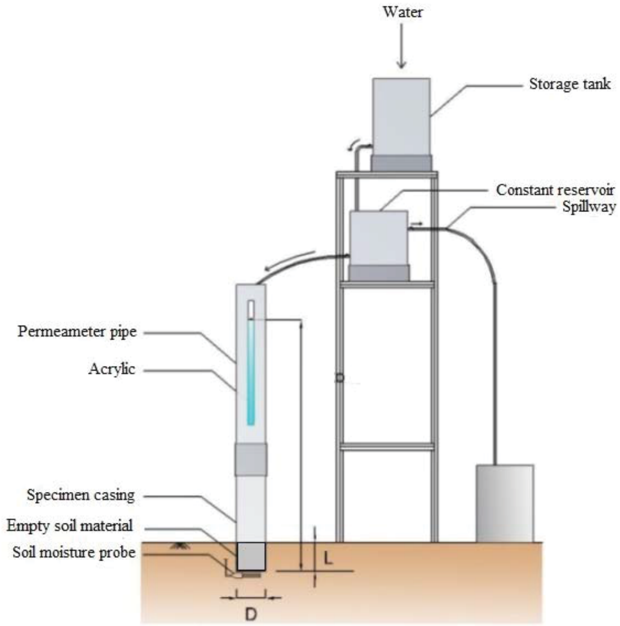

Fig. 5 Scheme of the permeability test instrument (*Constant Discharge model*)

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

$$k_{unsat} = \frac{\int_0^{z1} \frac{\partial \theta}{\partial t} dz}{\left(\frac{\partial h}{\partial t} + 1 \right)} \quad (4)$$

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. The value of hydraulic gradient was assumed to 1.0. Testing scheme is shown in Fig. 5. Values of permeability coefficient in unsaturated conditions were obtained from numerical models as [5] using:

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

$$k(S_e) = k_s S_e^{0,5} \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad (6)$$

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.

IV. Results and Discussion

A. Performance of Improved Constant Discharge Procedure

The results of field and laboratory permeability tests are compared to determine the level of data validation field test results. Test result data are presented in Table II. Based on Table II, the improved procedure result is consistent with the preliminary test indicates that the empty tube method produces permeability coefficient is smaller than the filled material tube method. Distribution of test data is shown in Fig. 6.

TABLE II
RESULTS OF IMPROVED METHOD

Point	K_{field} (cm/s)	$k_{laboratory}$ (cm/s)	Error
1	9.87 x 10^{-5}	1.50 x 10^{-4}	5.14 x 10^{-5}
2	7.94 x 10^{-4}	2.61 x 10^{-4}	5.33 x 10^{-4}
3	3.26 x 10^{-3}	3.01 x 10^{-3}	2.50 x 10^{-4}
4	1.20 x 10^{-3}	1.86 x 10^{-3}	6.77 x 10^{-4}
5	1.56 x 10^{-4}	4.35 x 10^{-4}	2.78 x 10^{-4}
6	1.22 x 10^{-4}	3.39 x 10^{-4}	2.16 x 10^{-4}

Field and laboratory test results have a margin and a relatively small error. The average difference of field and laboratory permeability coefficient is 3.33 x 10^{-4} cm/sec. Based on these data it can be seen that the results of the field test using an empty tube produce more valid data than the filled material tube method. Differences empty tube method test results and tube material contents indicate the level of influence the look of the test tube ends. End of the test tube looks directly affect the implementation on the ground and a geometric factor.

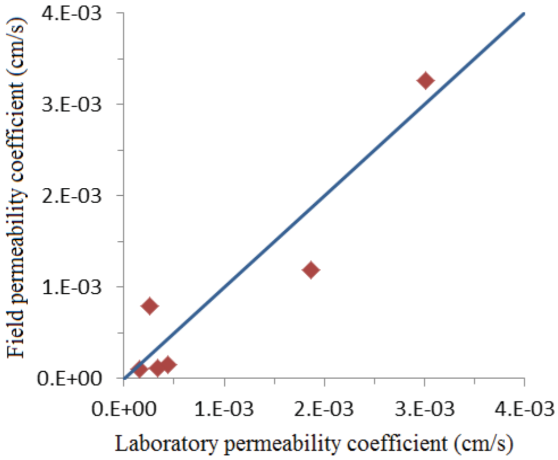

Fig. 6 Distribution data of testing result

B. Field and Laboratory Permeability Test Using Improved Procedure

Giving a constant water flow during testing, resulting in changes in the value of volumetric water content during the time of testing. It can be known from the results of the soil moisture sensor devices that have installed. From these values, it can be predicted a correlation between permeability coefficients (k) against volumetric water content (θ) using numerical approach. Value θ_s obtained from the value of the largest volumetric water content of the test directly in the field and value θ_r obtained from the current value of volumetric soil water content in dry conditions oven. While the value of n obtained from the database of software Hydruss-2D. The results of the field testing were compared with the results of laboratory testing for unsaturated soil conditions. Soil permeability testing in the laboratory to obtain permeability values unsaturated conditions carried out in accordance with the soil conditions, i.e. with a density of 15.5 kN/m^3. The results of these tests are the change of volumetric water content (θ) due process of wetting and drying process until dry conditions on the function of time as shown in Fig. 7.

The permeability coefficient of unsaturated soil conditions during the process of wetting can be estimated based on a numerical model that has been described by [5] using (5) and (6). Parameter θ_r is the residual value of volumetric water content obtained from the value of the water content of the soil in very dry conditions. In this study will compare the current value of the initial conditions θ_r in wetting process and θ_r in final drying conditions. The value of each condition in the amount of 6.6% and 23% by (5) and (6) and for the drying process used (4) to obtain a value of unsaturated permeability coefficient (k_{unsat}).

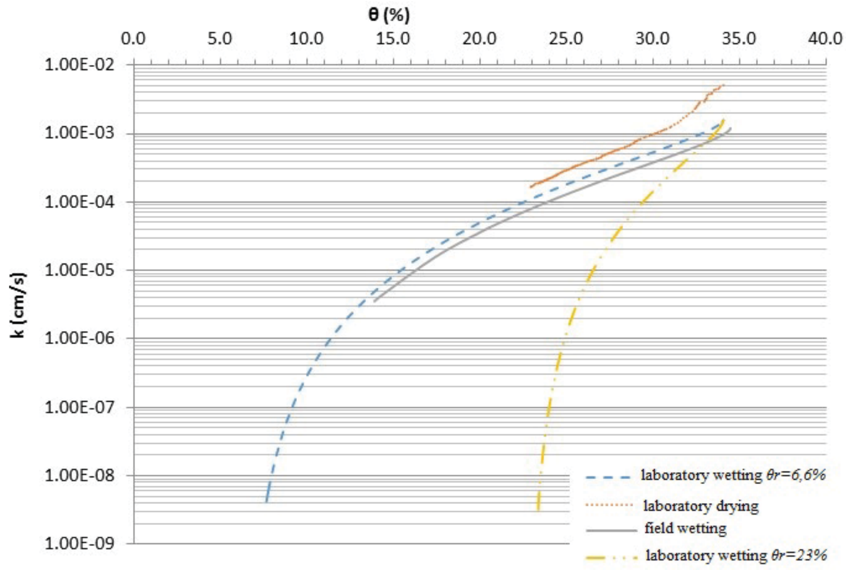

Fig. 7 Results of unsaturated field and laboratory permeability coefficient

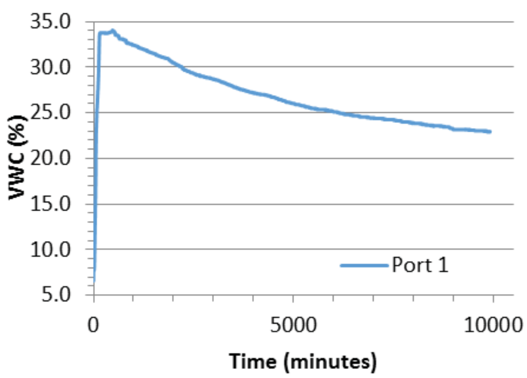

Fig. 8 Change of volumetric water content value over the time

Permeability coefficient is a value that indicates the ability of the soil to pass water. Soil permeability parameters necessary to know the speed of the water that seeped into the ground, therefore, the value of the units is equal to the unit value of velocity (cm/sec). This parameter is usually used to design a porous drainage channel and recharge wells. The coefficient of permeability of the soil that used as design parameter is always the value of permeability coefficient in saturated. However, in its development, the permeability in unsaturated conditions begins to be considered. That is because the conditions in the field are always changing depending on the value of the water content of the soil. Therefore, permeability values are necessary to know in unsaturated conditions that better represent in the field.

The results of permeability test under unsaturated conditions generate a graph that illustrates the process of volumetric water content changes over the time. Field test results in the changes of volumetric water content that is increasingly rising. This happens due to the wetting process occurs from the constant flow of water discharge. The wetting process that occurred in the field starts from natural soil moisture conditions until the soil is saturated. The soil is considered saturated when the value of volumetric water content is stable and the water level in the tube permeameter has not changed significantly.

The unsaturated permeability values from the field test result then compared with sample testing conducted in the laboratory. Laboratory testing conducted using the same method as in the field but started from oven dry soil conditions. In addition, testing was conducted in two processes that are a wetting and drying process. The wetting process is carried out from dry soil conditions until saturated and the volumetric water content values are stable. This was followed by drying processes ranging from saturation until the reduction of volumetric water content value is not significant. When the value of volumetric water content change has not significant, it can be regarded as naturally soil moisture in dry conditions without treatment.

Based on Fig. 8, the changes of the volumetric water content value have increased and then decreased. The increased process occurred because of the process of initial wetting. In this process, the permeability in unsaturated conditions also increased. That is because in the beginning of wetting the soil is still dry, water is flowing and filling pore cavities of soil that formerly occupied by air so that water cannot flow through the soil freely before the air pores completely filled with water. When the volumetric water content value decreased, it followed by drying process until the soil becomes naturally dry. In this process, unsaturated conditions permeability values decrease with the reduction of volumetric water content value that caused by cavity pores in soil that has been occupied by water was replaced again by air.

VG models as one determinant of unsaturated permeability coefficient needed some additional parameters that need to know from testing and modeling. Some parameters are required such that θ_s, θ_r, and n. In this study a comparison value of permeability coefficient (k) and volumetric water content (θ) shown in Fig. 7 with variations θ_r. Based on Fig. 7, it can be seen the effect of the higher value of θ_r generates more upright graphs. After changes of permeability values when the wetting process has known, it will be compared with the value of permeability when the drying process is obtained from (4).

Based on Fig. 7, the chart with a value θ_r = 23% is far below the graph for the drying conditions so that the value θ_r on the graph is not representative to determine the permeability coefficient. Besides the determination of θ_r with the natural dry assumption is also not suitable for dry soil because the soil still can dry out naturally in a long time. While the graph with θ_r = 6.6% is closer to the current chart drying process, when the oven dries soil conditions. However, there is a little difference permeability when saturated between wetting with drying condition.

Based on Fig. 7, unsaturated permeability coefficient with a density of 15.5 kN/cm^3 is ranging from 3,56x10^{-6} cm/sec (Sr = 31.1%) until 1,2x10^{-3} cm/sec (Sr = 77.06%). This value is taken in accordance with the field test result with a value below from the results that get in the lab. So field test result can be used as a reference to design a building that is expected to resolve the problem of the ponding area after rainfall.

V. Conclusions

Improvement of the testing procedure for in situ test to measure permeability under both saturated and unsaturated conditions was carried out. The improved testing procedure developed in this research was quite effective and more relevant than the previous result. Improvement of the geometric factor on the Constant Discharge Model makes the results more relevant to determine the permeability coefficient when compared with a standard laboratory test. The proposed constant discharge method can be used to determine soil permeability coefficient from unsaturated to saturated condition without establishing soil water characteristic curve.

Coefficient of permeability with field density of 15.5 kN/m^3 for unsaturated conditions was in range of 3,56x10^{-6} cm/sec (Sr = 31.1%) until 1,2x10^{-3} cm/sec (Sr = 77.06%) 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, field and laboratory test results had a mean difference of 3.33x10^{-4} cm/sec. The difference between the field and laboratory permeability test is very small, so that the data generate good results. This research is still in early stage. It needs further study on the wetting-drying cycle's effect on the soil. Further research about the influence of wetting-drying cycle's effect on the soil in unsaturated conditions due to water flow is needed.

Acknowledgment

The authors express their gratitude to Directorate General Higher Education (DGHE) Ministry of Education and Culture, Indonesia and Universitas Gadjah Mada for financial supporting by Competitive Grant of International Collaboration Research and Publication with contract no. LPPM-UGM: 1035/UN1-P.III/LT/DIT-LIT/2016, dated March 1, 2016. The authors also would like to thanks to colleagues of Department of Civil and Environmental Engineering, UGM and Preservation Center of Cultural Heritage, Prambanan Unit for their helpful and fruitful discussion and spirit in conducting field and laboratory tests.

References

[1] M.J. Hvorslev, Time Lag and Soil Permeability in Ground Water Observation. Waterways Experiment Station, 1951.
[2] L.A. Richards, Capillary Conduction of Liquids Through Porous Mediums. Physics, 1(5), p.318, 1931.
[3] A. Rifa'i, Y. Takeshita, and M. Komatsu, Development of In Situ Permeability Test Using Constant Discharge Method for Sandy Soils. World Academy of Science, Engineering and Technology International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, Vol:9, No:11, 2015
[4] Sunjoto, Optimasi Sumur Resapan Sebagai Salah Satu Pencegahan Intrusi Air Laut. In Seminar PAU-IT-UGM. Yogyakarta, 1988.
[5] M.T. van Genutchen, A Closed-form Equation for Predicting Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal, 44, pp.892-98, 1980.