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Infiltration Rate for Rainfall and Runoff Process with Bulk Density Soil and Slope Variation in Laboratory Experiment

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ABSTRACT

Water balance in urban drainage includes rainfall, runoff and infiltration. Rainfall, Runoff and infiltration are hydrology system units. They are processes which happened together; when rain falls, water will flow overland as runoff and the water that is lost infiltrates into the ground. The occurrence will involve several parameters, variables and treatments. Because the infiltration rate needs to be inquired from rainfall and runoff processes, the experiment was done using soil media with soil density and landslope variation. Meanwhile, the tool used for this experiment is Advance Hydrology of Rainfall Simulator. To determine the infiltration rate model, Horton's and Kostiacov's formulas were used. A positive correlation (R^2 = 0.91) of results for Horton formula was found, and a positive correlation (R^2= 0.813) was found in Kostiakov formula, demonstrating that the Horton and Kostiakov formulas were comparable to the observation of infiltration rate. Based on the observation result in laboratory, landslope and density are influential variable for infiltration rate. Infiltration rate will get smaller in the same density with increase landslope variation and it will also get decrease when soil density get higher. In contrary, decreased soil density creates increased infiltration rate.

INTRODUCTION

The infiltration equation has been developed for use in rainfall and runoff process (Parhi et al. 2007). Runoff procedures require separation of precipitation into excess rain and infiltrated rain. Infiltration models are based on the equations of flow through porous media would generally complicated in rainfall and runoff models. Infiltration is the missing piece in the flow of runoff that occurs, so the loss due to the infiltration process need to be assessed.

Infiltration depends on both the event and the soil properties. Differences in each infiltration model made from some formulas are caused by both the event and soil properties. The different values lie on the coefficient. For Horton formula, the value of k is the determining number for the event and soil properties. Meanwhile, for Kostiakov formula, it is the statistical completion for the number of k and a.

Horton assumes that infiltration rate will be influenced by the water content in the soil and the condition on the surface. Horton has also done research in infiltration rate on various soil events by relating rainfall and runoff process (Beven 2004). Then, Kostiakov infiltration function is calibrated for specific field conditions (Furman et al. 2006), so the both formulas need to be checked for the accuracy to calibrate the observation result in the laboratory using soil density and landslope variations.

The objectives of this paper are to obtain the infiltration rate model from rainfall and runoff process with event in soil density, soil properties and landslope; and to inquire the use of Horton formula and Kostiakov formula compared with infiltration rate from observation using soil treatment in laboratory done by sprinkling, with rainfall simulator (Furman et al. 2006).

The essential originality of this model is to determine infiltration rate from rainfall and runoff curve model. And the determining variable for infiltration rate are soil density variation made in laboratory experiment and landslope set in rainfall simulator. Then, the observation result model verification is done by using Horton's formula that is usually used to predict infiltration rate in the field, which is then compared with Kostiakov's formula (Estevesa et al. 2000).

Infiltration is the process by which water arriving at the soil surface enters the soil. This process affects surface runoff, soil erosion, and groundwater recharge. Being able to measure the surface infiltration rate is necessary in many disciplines. Horton's formula is still very efficient for various events to get infiltration model. As quoted (Beven 2004), Horton states that when the rain falls, infiltration capacity will be influenced along with water content condition in the soil. Horton introduces his basic ideas about infiltration capacity as a control on surface runoff and the consequent possibility of subdividing the discharge hydrograph into two components, that of surface runoff derived from the 'rainfall-excess' and that of ground-water flow that is maintained by the water infiltrated into the soil.

Horton's Formula is:

$$f = fc + (fo - fc)e^{-kt} \qquad ...(1)$$

i ≥ fc and k = constant
f = infiltration capacity
fc = minimum constant infiltration capacity (cm/h)
fo = infiltration – capacity at time t = 0
t = time
k = constant for given curve

Horton's equation might be considered a quasi unsteady analysis because, although he used the same basic equations as those for kinematic wave theory, he assumed that the water surface profile was always geometrically similar to the equilibrium profile (Allen 1981).

If capillary pull at the moist front within the soil was the only factor involved in the change of infiltration-capacity with time during rain, then differences in soil cover and surface treatment should have little effect in cases, where, as is often true, the depth of moisture penetration is below the depth of surface treatment (Horton 1940: 404) in (Beven 2004).

Kostiakov's model uses power function model approach without inputting the initial water content and saturated water content (at constant infiltration rate) as functional component. The model is better in data prediction in the field with varied characteristics (Mbagwu 1997). Infiltration function model infiltrasi and infiltration rate are presented in the formulas below:

$$F = at^b, \ 0 < b < 1 \qquad ...(2)$$

$$f = \frac{dF}{dt} = abt^{b-1} \qquad ...(3)$$

Where a and b are constants. They depend on soil characteristics and initial water content. These constants cannot be determined before and usually determined by drawing a straight line as power in statistics model. The line is for empirical data and used for east square method (Cahoon 1998).

The density is land surface event that becomes one of the factors influencing infiltration rate. Soil density is appraised by bulk density. Bulk density depends on soil organic matter, soil texture and the density of soil mineral (sand, silt, and clay) (USDA-NRCS 2015). Bulk density can be changed by management practices that affect soil cover, organic matter, soil structure, compaction and porosity.

The soil bulk density (BD), also known as dry bulk density, is the weight of dry soil (M_{solids}) divided by the total soil volume (V_{soil}). The total soil volume is the combined volume of solids and pores which may contain air (V_{air}) or water (V_{water}). Infiltration will decrease as density value gets bigger, and infiltration will increase as density value gets smaller. High bulk density is an indicator of low soil porosity and soil compaction. Compaction increases bulk density and reduces crop yields and vegetative cover available to protect soil from erosion. By reducing water infiltration into soil, compaction can lead to increased runoff and erosion from sloping land or saturated soils in flatter areas (Mbagwu 1997).

Soil density equation:

$$\gamma_d = \frac{\gamma_b}{1 + w} \qquad ...(4)$$

The γd is the weight of dry soil per unit of volume.

Consequently, simulations can start on an initially dry surface and handle calculation on dry and wet areas allowing a more realistic prediction of the interaction between rainfall, overland flow and infiltration.

MATERIALS AND METHODS

Data and measurement site: In this study, the infiltration rates were collected at rainfall simulator with rainfall and runoff process. Rainfall was setted on 2 litre/minute. And runoff time of data from rainfall simulator were setted during 2 hour. The method to measure the infiltration rate is using sprinkling. Sprinkling method is using a plot of treated soil which is used to simulate rainfall and to calculate how rain relate to time. Altogether, it will result in runoff and will discover the loss of infiltration. Sprinkling method is used on rainfall simulator. It is artificial rainfall simulator to get infiltration in different degrees of slopes. On this device (Fig. 1), it can provide steady rain.

First of all, soil was dried by sun drying. After soil becomes dry, it was ground until the granules were refined and then filtered using in tenth sieve to obtain good soil condition to do research of rainfall simulator running. After the soil manage the tenth sieve, the soil was given 20% of water and then the soil is tested for the water content.

The soil weight is 120 kg to be put in to tank with 0.97

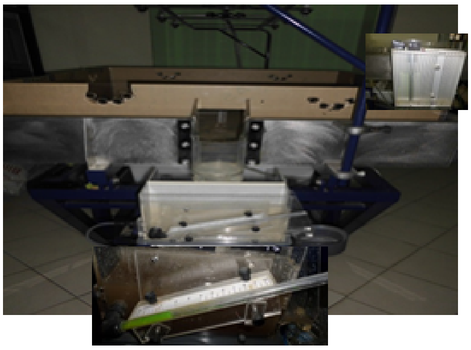

Fig. 1: Rainfall simulator.

Fig. 2: Compaction process in laboratory.

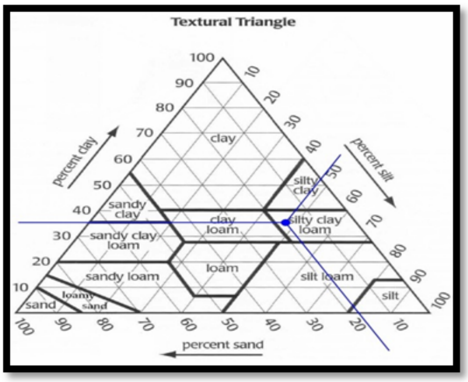

Fig. 3: Clarification based on textural triangle (USDA).

× 1.17 × 0.3 meter long. The upper part of this tank has nozzle that can adjust the size of the rain drops. This test tank also has two pipes with big pores in the base. This tank also has two water channels connected to the other tanks with current measurement, in which each channel can be measured. Under the tank, it has piezometric tube test, that allows to see water level every time.

Soil properties observed are the texture, water content, the specific gravity, soil bulk density and porosity. The method of hydrometer is used for soil texture observation while soil sample is taken for observation of water content, the specific gravity, soil bulk density and porosity.

The density variable is modified into light, medium and heavy and by taking one particular kind of soil. The observation is also done by setting land slope. The both variables mentioned are taken for rainfall, runoff and infiltration process. Light density is treated in laboratory by compacting the soil in two around, the medium in four around and the heavy in six around. Determining how many rounds should be done is based on one previous study on the same soil. Soil is treated in silider Proctor in which six compacting rounds have the same value with twenty four compacting rounds (maximum density). The soil is made into 3 layers of light, medium and heavy densities. Equal height every side is obtained by using round. The process in rainfall simulator is shown in Fig. 2.

In the laboratory, preparation is done by setting soil density and slope. Each density expose to a variety of slope: 2%, 3% and 4%. This density modification is for laboratory condition simulating the field condition where vehicles, pedestrian, and other natural agents are creating the density.

RESULTS AND DISCUSSION

Soil sample taken is examined in laboratory using hydrometer to find the particles size (sand, silt and clay), specific gravity of soil, void ratio and porosity. The result of the examination are given in Table 1.

The composition can be clarified by USDA (United States Department of Agriculture) and the result is shown in Fig. 3.

And then, from the result above it is learnt to fall soil into the category of silty clay loam. Testing of soil density by weight of the dry soil divided by the volume of compacted soil . Variation of soil density is carried out in laboratory with pulverization and a number of turns. Pulverization is carried out to 3 layers. Each layer is pounded with a pestle weighing 2.9 kg. Each compacted soil with different rotation will result in a decrease from the initial height. The initial height of 120 kg soil without layers is 14.7 cm.

Decrease in height of each layer after pulverization is given in Table 2.

Numerous experimental data show that even in such cases where there is a marked variation of infiltration-ca-

Table 1: Soil particles size composition.

Location	Soil particular size (φ)		
	Sand	Silt	Clay
	(%)	(%)	(%)
Tlogomas	18.0	46.8	35.2

Source: Calculation result

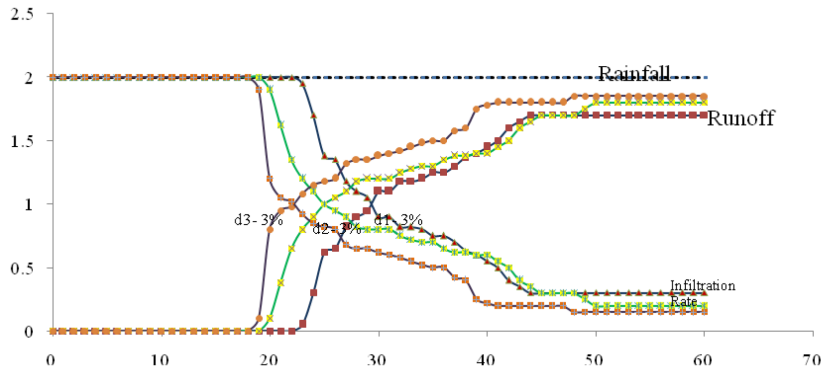

Fig. 4: Observation result of rainfall, runoff and infiltration process for soil density variation (d1, d2, d3) and 3% slope in rainfall simulator.

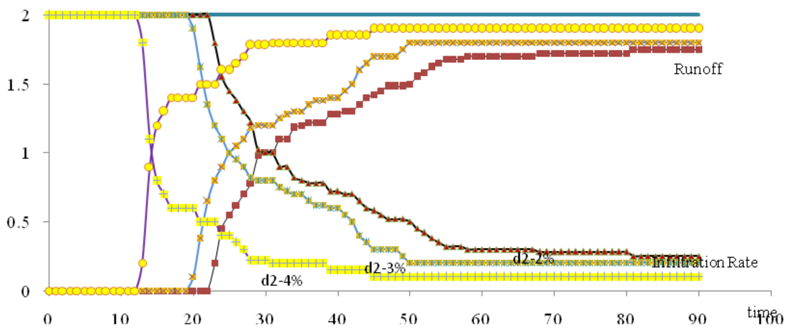

Fig. 5: Observation result of rainfall, runoff and infiltration process for slope variation (2%, 3%, and 4%) and density soil d2 in rainfall simulator.

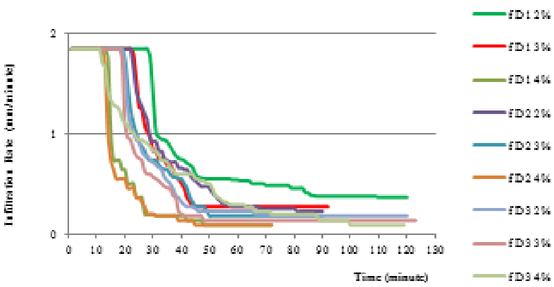

Fig. 6: Different infiltration rate influenced by density of soil and slope.

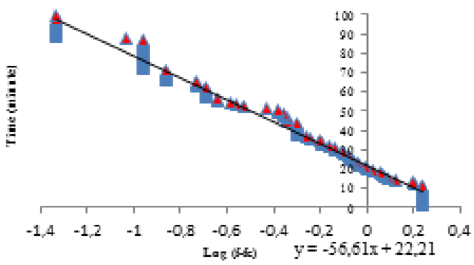

Fig. 7: Comparison curve of log(f-fc) with time (minutes).

pacity for the same soil, with the same depth of penetration with different types of cover and different surface treatments. Compaction increases bulk density and reduces total pore volume, consequently reducing available water holding capacity.

The data obtained are the primary data from a laboratory using a Rainfall Simulator with variations in the density of the soil and the slope of the land. Based on the factors that influence the runoff process then determined the conditions laid down for this runoff data retrieval that is based on the physical properties of the soil, the slope of the land, the behaviour of the density of the soil and rainfall intensity. Results of observations in the runoff Rainfall Simulator tool are shown in Fig. 4; it is to a density of 2 rounds (d1), 4 rounds (d2), and 6 rounds (d3) with a slope of 3%.

Base on the observation result above, it is learnt that infiltration rate will get lower as the soil get more densified with the same slope. Then, the next observation is done with land slope variation in the same density, the result is as shown in Fig. 5.

The observation result of rainfall, runoff and infiltration proceses for slope variation and density soil d2 in rainfall

Table 2. The result of soil bulk density.

Density Technique	Solid Weight (Ws)	Decrease in height after pulverization (cm)	Volume cm^3	*Ws/Vgr/cm³*	*Water Content (w)*	γ_d *(Bulk Density Soil) g/cm³* $\gamma d = \frac{Ws}{V(1+w)}$
2 rotation	120kg	13.43	145512.707	0.83	19.00	0.697
4 rotation	120kg	11.685	136702.44	0.95	23.37	0.774
6 rotation	120kg	10.48	124384.65	1.06	28.74	0.8233

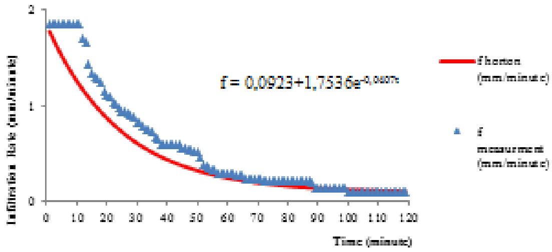

Fig. 8: Comparison curve of infiltratin rate and time using Horton formula.

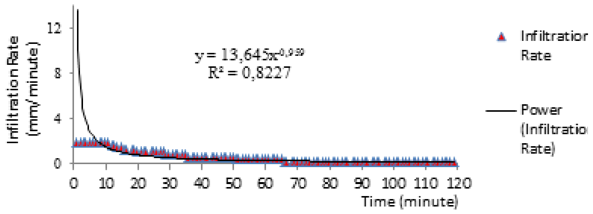

Fig. 9. Infiltration rate curve d3 4% with Kostiacov formula.

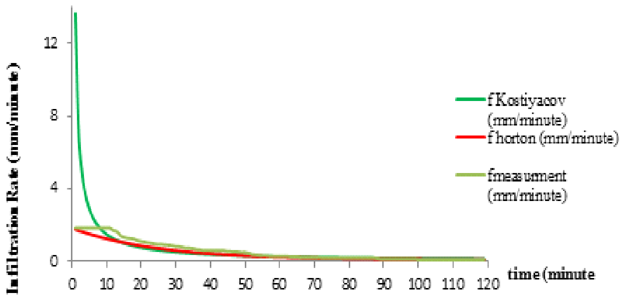

Fig. 10: The curve of infiltration rate Kostiacov and Horton Model compared to measurement result.

simulator, that infiltration rate will get lower as the land slope becomes more with the same density and the same soil characteristics.

Based on the observation of infiltration rate above with variation of density and slope, both of them influence infiltration rate. Rainfall Simulator was a reliable method for estimating water infiltration rates while successfully incorporating an element of simulated rainfall, potentially rendering tests more realistic (Peter et al. 2014).

Table 3: The effect of density of soil and slope on infiltration rate.

Name of Sample	Slope (%)	Density (yd) (g/cm³)	Constant infiltration rate (mm/minutes)
d1	2	0.697	0.3692
d1	3		0.2769
d1	4		0.0923
d2	2	0.774	0.2307
d2	3		0.1846
d2	4		0.0923
d3	2	0.823	0.1846
d3	3		0.1384
d3	4		0.0923

Examination of infiltration rate in rainfall simulator shows that the infiltration rate will decrease as time accumulate. The longer it takes for infiltration, the soil layer will get more moist and become saturated, so the soil is unable to absorb water any more.

Infiltration rates on particular soil density and land slope influence the time for soil to absorb water which lead to constant infiltration rate, as shown in Table 3 and Fig. 6.

Deciding infiltration model with Horton Formula in D3, 4%, results are in Fig. 7.

Formula taken from the curve above is:

$Y = -56.61x + 22.21$

The formula is used to find k value. The k value is as follow:

$k = (-1 / 0.434m)$

$= (-1 / (0.434 \times -56.61)$

$= 0.0407$

So that, infiltration model formula with Horton Formula is:

$f = fc + (fo - fc) \times e^{-0.0407t}$

and infiltration rate model with Horton formula is:

$f = 0.0923 + 1.7536 \times e^{-0.0407t}$

It can be seen in Fig. 8.

Infiltration model using Kostiacov model is shown in Fig. 9. Formula obtained is Kostiacov model formula which is $Y = f = 13.645t^{-0.959}$. The X value is taken from time. Next, the result of infiltration rate measurement compared to Kostiakov model and Horton Model, is as shown in Fig. 10.

From the measurement result, with the average relative error analysis, the model result similar to infiltration rate measurement in rainfall simulator is Horton model formula with the average value of relative error of 8.98% and Kostiakov model with the value of relative error of 18.74%.

Kostiakov Model with the average value of relative error 18.74%, is proved to be more erroneous in spite of the fact that it is commonly used in laboratory experiment.

CONCLUSION AND FURTHER STUDY

Infiltration rate is highly influence by landslope. A steeper landslope result in a smaller infiltration rate. Whereas, a slighter slope result in higher infiltration rate. Observation result on the same density of ($c_{d=}$0.697 g/cm^3) by varying landslope is as follow: f d1 2% result in 0.3692 mm/minutes, f d1 3% result in 0.2769 mm/minutes, f d1 4% result in 0.0923 mm/minutes. Second conclusion is that infiltration rate is significantly influenced by density. A higher density result in a smaller infiltration rate. On the contrary, smaller soil density result in higher infiltration rate. Observation result on the same slope of 2% by varying soil density is as follows d1 2% result in 0.3692 mm/minutes, f d2 2% result in 0.2307 mm/minutes, and f d3 2% result in 0.1846 mm/minutes.

The results showed that a good match between measured and observed surface runoff and total drainage does not guarantee accurate representation of the flow process. And Horton model which is commonly applied on field experiment in this laboratory observation turns out to result in similar measurement result of rainfall simulator compared to Kostiacov model.

In measuring infiltration rate in laboratory, land slope variation should be given more, it is suggested to give more variation of landslope, soil density, and rainfall intensity to strengthen the purpose of result. For the infiltration model, it is suggested to be added and compared to the other model, so it can produce a new model of infiltration rate for density and slope given.

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