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Numerical Assessment of Rainfall Infiltration into Soil Column for the Unsaturated Layered Residual Forest Soil

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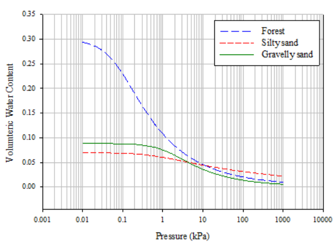
Graphical abstract



Abstract

Infiltration caused by rainfall leads to the changes of moisture content and pore water pressure of the soil. These changes indicate the behavior of the soil especially during wetting and drying due to rainfall. This paper describes the numerical analyses and result of rain water infiltration into soil column using SEEP/W (Geo-Slope International, 2004). The analyses were using three types of soils.Two types of soils were commercially obtained;siltyand gravelly sand, while another soilsample obtained from UniversitiKebangsaan Malaysia (UKM) forest. The main objectives are to describe the rainfall infiltration behavior into unsaturated residual forest soil, using one-dimensional soil column model, and the effect of rainfall intensity and duration to the infiltration process for the soils. The soil properties used for that analyses such as soil water characteristic curves (SWCC), and hydraulic conductivity were obtained from the laboratory works. The study was performed for one, three, and six hour flux for all types of soils.Results of volumetric water content show that water infiltration in silty and gravelly sand aremore rapidly than forest soil. The upper layer of soil column experienced greatly increased of volumetric water content compare to the other layers.In addition, pore water pressure for siltyand gravelly sand has also greatly increased from negative towards positive value for one and three hour rainfall compared to forest soil. Therefore, as the water infiltrates,initially dry soil will gradually increase both volumetric water content and pore water pressure as an event of rainfall is applied.

Keywords: Infiltration; matric suction; volumetric soil moisture; soil column

■1.0 INTRODUCTION

1.1 Background

Rainfall is the main reason that leads to the decreasing of soil's shear strength in the tropical country. Decreasing of soil strength will lower the factor of safety against soil stability especially for slope. Residual soil which covers most of tropical country is subjected by climatic and hydrological changes such as precipitation, infiltration, evaporation and transpiration (Rahardjo *et al*. 2010). The negative pore water pressure forthese type of soil is normally located above the groundwater table.

In a rainfall event, some of the precipitation that reaches the soil surface will penetrate into the soil which is called infiltration, while some will become the surface runoff. Under unsaturated condition, the pore water pressure below the water table which is in positive value, will rise depends on the infiltration rate, intensity and duration. On the other hand, the negative pore water pressure which at the upper side of the ground water table will decrease. The changes of the pore water pressure subsequentlywill vary the structure of soils, and decrease the frictional and cohesive strength between soil particles(Gofar *et al*. 2006). Therefore, higher intensity and duration of rainfall in an event will lead to the higher infiltration rate through the soil and consequently lower the factor of safety against slope instability (B.K *et al*. 2006,Gasmo *et al*. 2000,Kassim *et al* 2008).

However, Lee *et al*. (2011) and Mukhlisin *et al*. (2008 and 2011) mentioned that the residual soil behavior is complex due to the soil parameters such as soil initial moisture condition, soil water retention ability, soil porosity, evaporation rate and others. Residual soil is also considered in high nonlinearity of soil water characteristic and soil permeability (Yang *et al*. 2006). Therefore, it is essential to study the infiltration mechanisms in order to comprehend the behavior of soil under various rainfall intensity and duration, with the intention that the parameters mentioned can be obtained.

Experiment of water infiltration into the soil using soil column apparatus was extensively used in the geotechnical study. The understanding of the parameters' complexity in rainfall infiltration for the unsaturated soil can be facilitated using soil column apparatus. Normally, studies using soil column are conducted by means of rainfall intensity and duration to the soil. Soil water redistribution and hysteresis phenomenon which is vital in understanding the unsaturated soil study can also be explored (Yang *et al*. 2006and Indrawan *et al*. 2007). A study of unsaturated soil on transient of pore water pressure distribution and redistribution of rainfalls were done by Lee *et al*. (2011).

It was mentioned before that study of rainfall infiltration into the unsaturated soil is complex in term of parameters that need to be obtained. Therefore, the numerical simulation performing these phenomenon is needed, which parameters and behavior of the soil can be predicted. Thus,the parameters can be used to facilitate the results obtained in the geotechnical problem especially in the study of soil instability.

1.2 Previous Studies

Many studies have been done to investigate rainfall infiltration of unsaturated soil column. Rahardjo *et al*. (2010)described the use of SEEP/W for the response parameters in the soil column which are wetting front, matric suction reduction depth, and sectional infiltration rate. The results showed that the proposed parameter can be used as an approximate alternative or indicator in quantifying the potential impact of rainwater infiltration.

A study by Kassim *et al*. (2008) used SEEP/W as a simulation tool for two layer of soil column, a layer of silty sand over fine sand, and a layer of silty sand over gravelly sand. The results showed that the formation of the soil influenced water infiltration into the soil. The barrier effect of the soil wasclearly identified when the difference of permeability and pore water pressure transforming across the soil column from the finer to coarser soil boundary.

Simulation for rainfall infiltration into soil column on hysteretic model using SEEP/W was accomplished by Yang *et al*. (2012). The study which was done on layered soil column, demonstrated the vital role in the seepage analysis of unsaturated soils which is subjected to drying and wetting process. There were also other studies using other than SEEP/W (Geostudio) in obtaining parameters through numerical simulation. Indrawan *et al*. (2007)studied two layers of soil column using SV Flux (Soil vision system ltd 2003) to compare the result obtained by experiment of water infiltration. They found that, stagnant non-equilibrium profiles of pore water pressure head were obtained in the gravelly sand soon after a drying process started.

Ma *et al*. (2010)used Green-Amp model and HYDRUS - 1D code which investigated water infiltration based on Richard's equation for a layered soil. This study was done to simulate five layers of soil column which tracked the wetting front and infiltration rate, and cumulative infiltration. However,the result indicated that water infiltration process predicted using Green-Amp model was unable to give sufficient results compared to HYDRUS -1D. For that reason, in the study, theresearcher focused only on the simulation based on the infiltration rate and cumulative infiltration.

1.3 Objectives

In this study, parameters of unsaturated forest soil of UniversitiKebangsaan Malaysia (UKM), silty and gravelly sand were obtained through numerical simulation. There were many landslide events occurred in the UKM campus area recently. The main reason for the landslide events was believed to be caused byintense rainfall and water infiltration prior to the landslide events. The main objective of this paper is to describe the rainfall infiltration behavior into unsaturated residual forest soil, using one-dimensional soil column model. Therefore, the studywill discover the effect of rainfall intensity and duration to the infiltration process of the soils. The pattern of the volumetric water content and pore water pressure of the forest soils are compared to the two other types of soils that were commercially obtained; silty and gravelly sand.

■2.0 MATERIAL AND METHOD

2.1 Determination of Soil Properties

In this study, soil properties determination is needed prior to the simulation. The soil properties such as saturated conductivity, $K_s$and soil water characteristic curves (SWCC)were determined from three samples. It is noted that the undisturbed samples forest soil were obtained from the site located near the Faculty of Engineering and Built Environment, UniversitiKebangsaan Malaysia (UKM). Meanwhile, the other soils were commercially obtained, and repacked for the purpose of testing.

The ability of soil's to transmit water or saturated hydraulic conductivity, K_s, wasobtained using constant head permeability method,according to the standard procedures outlined by ASTM D2434-68(2006).For the forest soil, undisturbed samples were obtained, while for silty, and gravelly sand, samples were repacked for the experiment.

Volumetric water content and pore water pressure relationship for the soils were determined by SWCC. In this study, Plate Pressure Extractor (PPE) apparatus wasused toobtainSWCC. The saturated soil samples were placed in the chamber and pressure were applied in the range of 0 to 1500 kPa. In this study, Van Genuchten (1980) empirical method which iscurving fitting technique of nonlinear for soil hydraulic modelswas used to best fit the result obtained from the experiment. Hence the fitting parameters for SWCC for all samples were determined. Result for SWCC parameters, and soil properties obtained are shown in the Table 1, while the SWCC and hydraulic conductivity curves are shown in Figures1, 2(a),and (b) respectively.

Table 1 Soil properties and parameters

	Symbol	Forest Soil	Gravelly Sand	SiltySand
Saturated volumetric water content (kPa)	$\emptyset_s$	0.2988	0.0883	0.0697
Residual volumetric water content (kPa)	$\emptyset_r$	0.2427	0.0313	1.7993e-07
Fitting parameter	α	0.0719	1.2931	0.5340
	n	1.3924	1.4396	1.1550
	m	0.2818	0.3054	0.1342
Saturated hydraulic conductivity (m/s)	K_s	3e-06	6.333e-4	1.149e-3

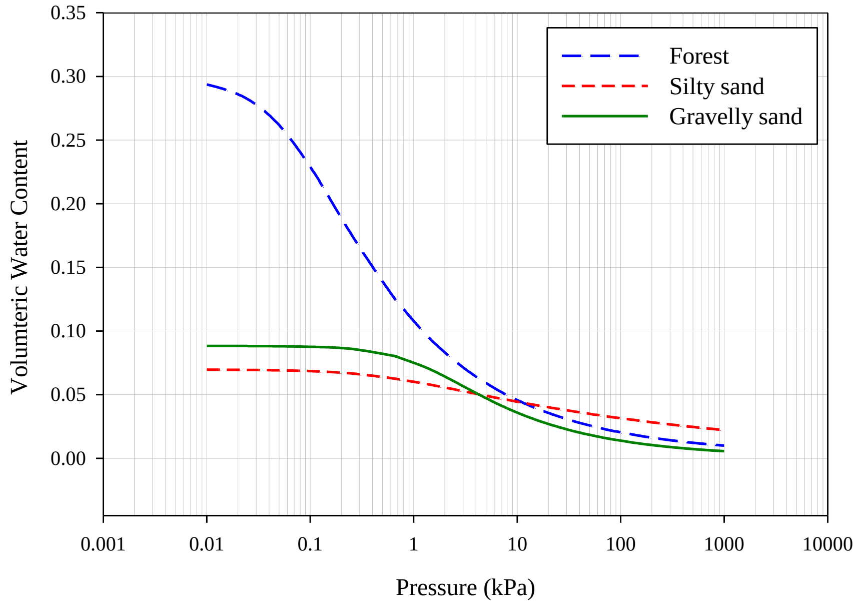


Figure 1 SWCC of the soils

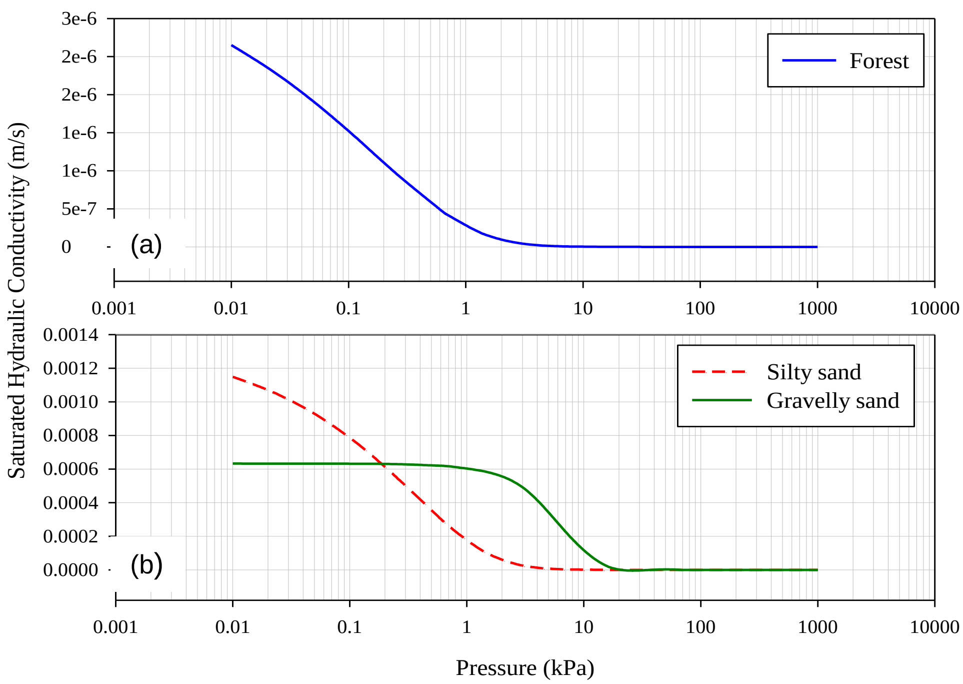


Figure 2 Hydraulic conductivity of the (a) Forest soil (b) Silty and Gravelly sand

2.2 Numerical Simulation

In this study, the numerical simulations of infiltration in the soil column were performed using the finite element model. This vertical one-dimensional soil column analyses were performed for a 200 mm diameter x 1m deep soil column for all samples. For the infiltration analysis, the simulations were done for both steady state, and transient condition. Steady state analysis was performed in order to obtain the initial condition of the soil column, while transient analysiswas for the infiltration process.

In this model, the boundary condition of the soil column must be identified for adequate simulation. For the steady state analysis, the boundary condition of *h*=10 m at the top and bottom of the soil column were assigned. On the other hand, for the transient analysis, simulated rainfall was assigned at the top of the column with the influx boundary condition of q = 0.023m/s.Meanwhile, the bottom boundary condition was assigned as atmospheric pressure.All analysis of soil column was done for 3 period of time; 1, 3 and 6 hour duration of rainfall as in Figure 3.The model of the simulation is as shown in Figure 4.

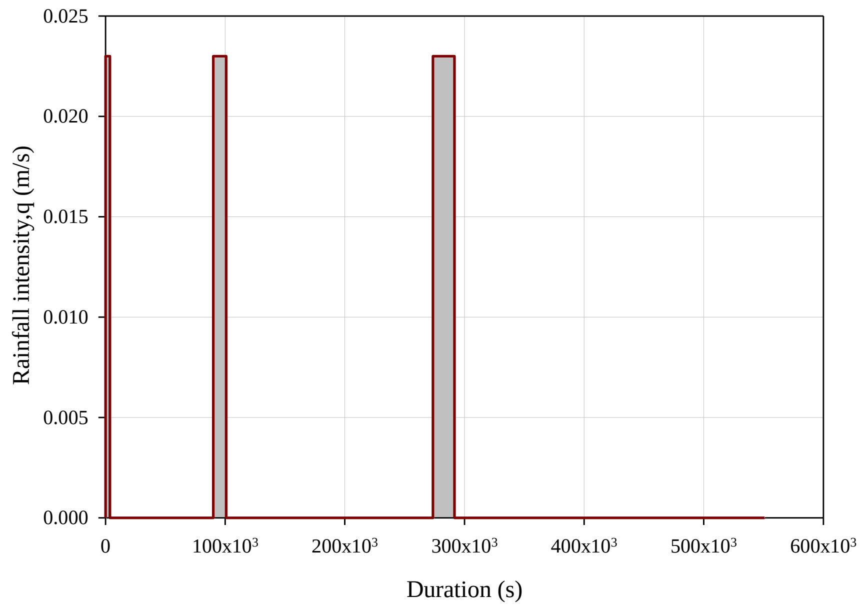


Figure 3 Hyetograph of applied rainfall

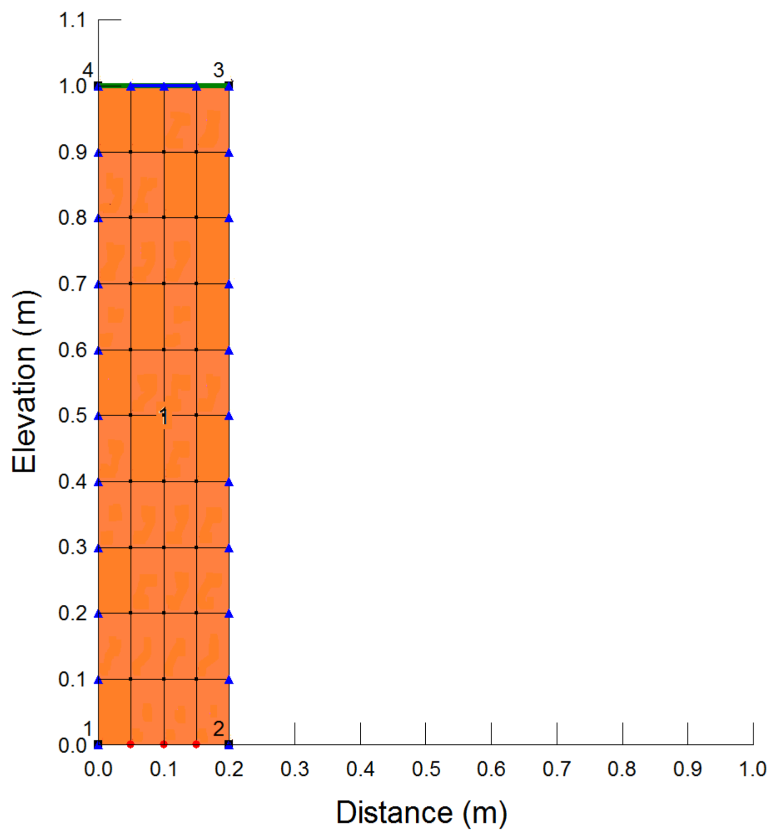


Figure 4 Simulation model of soil column using SEEP/W

■3.0 RESULT AND DISCUSSION

The results of numerical simulation are presented in term of volumetric water content vs. elevation, and pressure vs. elevation as shown in Figure 5 and 6.

3.1 Volumetric Water Content

In general, wetting fronts for all types of soils started from the top of the column as the rainfall applied, then the wetting process gradually increased the volumetric water content at the middle and the bottom layer of the column. From Figure 5, it was observed that for the forest soils, by applying 1 hour rainfall and 24 hour drying process, the infiltration only affected the top layer of the soil (Figure 5a). But, for the 3 hour rainfall, water started to infiltrated into the middle layer of the column (Figure 5b). Furthermore, water infiltration continuesuntil reachedthe bottom layer for 6 hours rainfall as shown in Figure 5c.It was noted that it takes about 80 hours for the water to infiltrated into the soil from the top to the bottom of the soil column.

For gravelly sand, the pattern of volumetric water content was gradually moved to the right as the rainfall applied (Figure 5d).It was observed that after 1 hour rainfall, the water infiltrates throughout the column in 6 hours (Figure 5d). On the other hand, for the 3 hour rainfall, the volumetric water content was greatly increased throughout the soil column after 1 hour rainfall was applied (Figure 5e). From the Figure 5(f), it was observed that towards the drying process, the volumetric water content for upper layer of the column was stagnant, but continues to increase for the bottom layer as the water continues to infiltrates.

Meanwhile, water infiltration for silty sand showed the increasing of volumetric water content from 1 hour to 6 hour rainfall to the soil column at the top layer. Even though the graph as in Figure 5g, h and i shows the increasing value of volumetric water content, it was noted that the changes were very small especially at the bottom layer of the soil.

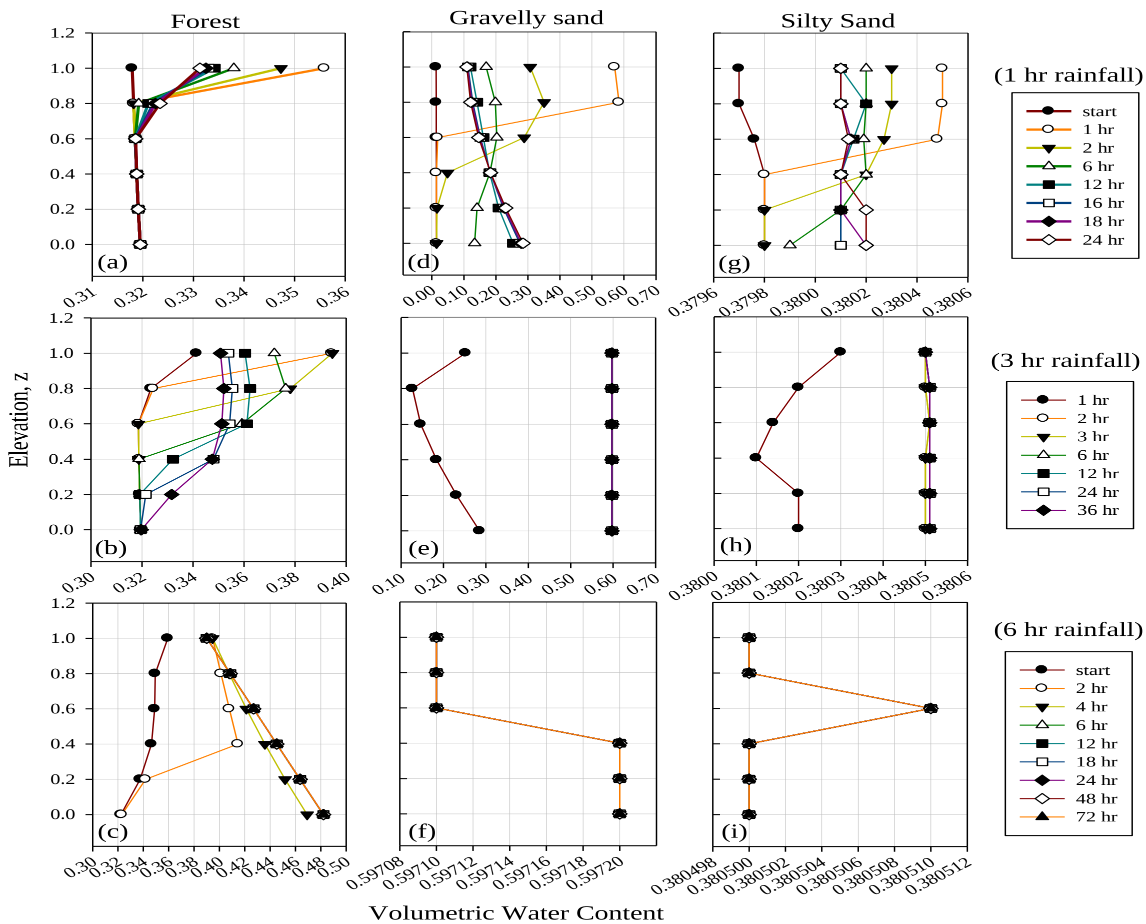


Figure 5 Volumetric water content for Forest soil, Gravelly and silty sand for 1 , 3 and 6 hr rainfall

Therefore, it can be concluded that the results obtained in Figure 5 were in a good agreement with the SWCC results obtained as in Figure 3. The figure showed that based on the SWCC, types of soil influence its water holding capacity which can be related to the ability of water infiltration water infiltration in the soil column. Infiltrations for the coarser soil such as gravelly sand and silty sand were faster than finer soil such as forest soil. Meanwhile, volumetric water content for the upper layer of the soil will increase greatly compared to the middle and the bottom layer,as the wetting process started.

3.2 Pore Water Pressure

In general, as the water infiltrates into the soil column, result shows the increasing of pore water pressure, indication pattern that moved to the right of the graph. For the forest soil, as the

rainfall applied to the soil, pore water pressure was increasing from negative towards to positive value (Figure 6a).
It was observed that the increasing of pore water pressurewas only at the top layer of the column for the 1 hour rainfall. For 3 hour rainfall, the results showed that pore water pressure continue to increased at the middle layer of the column, and finally as the water infiltrates, the pore water pressurealso increaseat the bottom layer. It took about 80 hours for water to infiltrate from top to the entire layers which was after the 6 hours rainfall (Figure 6b and c).

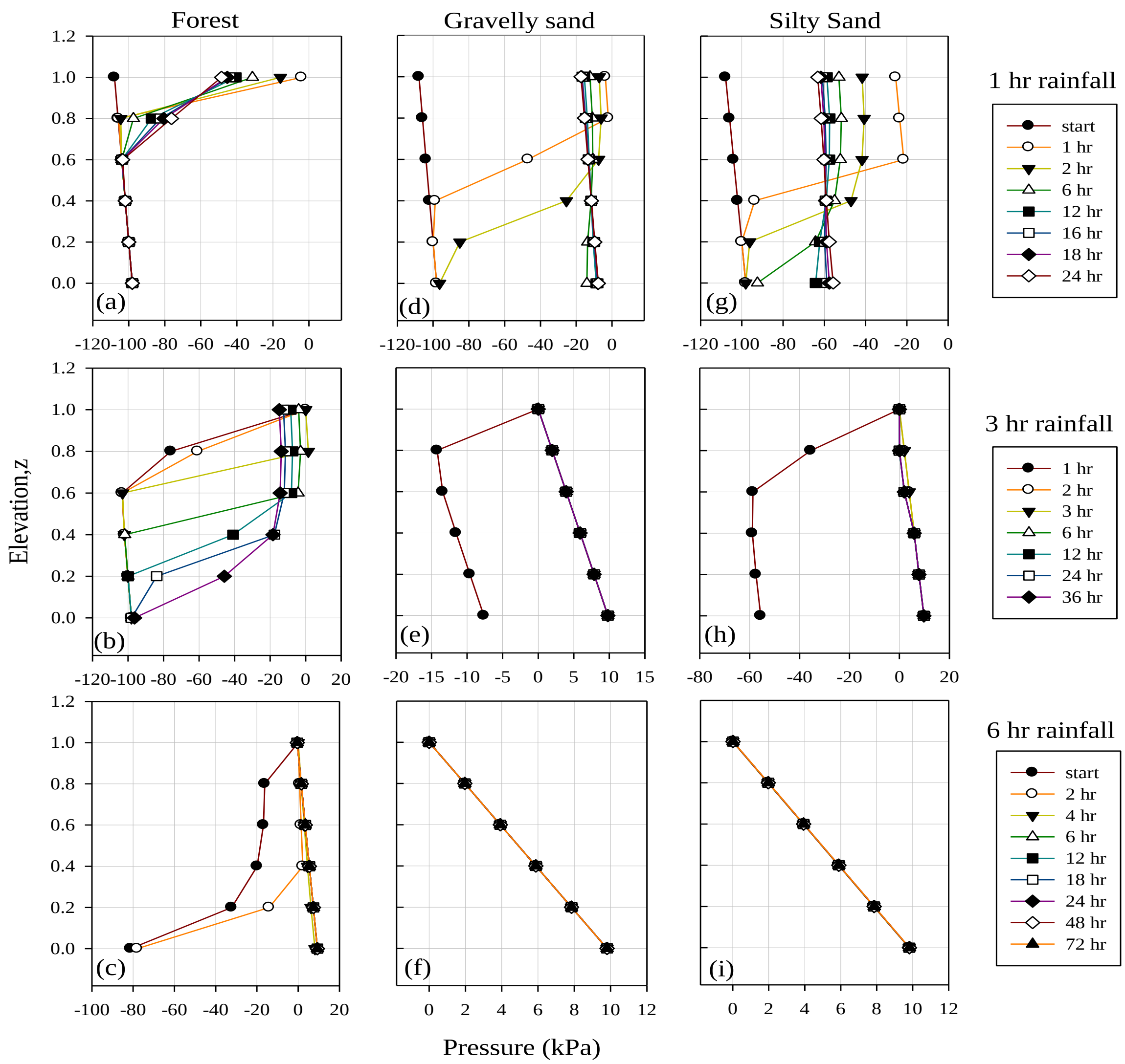


Figure 6 Pore water pressure for Forest soil, gravelly and silty sand for 1,3, and 6 hours rainfall

For the gravelly sand, for 1 hour rainfall,the increasing of pore water pressureat the top and middle layer was after within 2 hours. The bottom layer of the column started to increase after 6 hours which wasduring the drying process. For 3 hour rainfall, the value of pore water pressure continued to increasedand stagnant until the 6 hours rainfall is applied. At the end of the drying process, the pore water pressure at the bottom layer is observed to be higher than the top layer. The phenomenon is believed to be due to the drying process where water infiltrates from top to the bottom layer of the soil column.

According to the result obtained, silty sand experienced the increasing of pore water pressure at the top of the soil column as one hour rainfall was applied. As the drying process continues, the pore water pressurealso continues to increase at the middle layer towards to the bottom layer. The increasing of pore water pressure at the bottom layer started after 12 hours which was during the drying process. Neverthelessvalue of pore water pressure started to stagnant after 6 hours rainfall was applied. However, at the end of the drying process, the pore water pressure at the bottom of the soil column was perceived to be higher than the top layer due to the water infiltration which continues from top to the bottom of the soil column.

■4.0 CONCLUSIONS

Infiltration tests were numerically simulated to describe the behavior of soils. There are three types of soils such as forest soil, gravelly sand, and silty sand, were examined with selected intensity for the simulation. Soils were simulated and compared in term of the volumetric water content and pore water pressure. The volumetric water content results obtained through numerical simulation show that types of soils influence the water infiltration process in the soil column. Infiltrations for the coarser soil such as silty and gravelly sand aremore rapidly than finer soil such as forest soil. Other than that, volumetric water content for the upper layer of the soil where wetting process started will greatly increasecompared to middle and bottom layer. The increasing value of pore water pressure indicates the saturation of soil. As the saturation increased, the pore water pressure value which is negative initially will increase to positive value. The increasing of these values continuously gradually as the rainfall applied, affect the soil strength and instability.Results also show that generally, pore water pressure in all sections in soil column were changed due to the boundary condition applied. In contrast, the top section in the soil column was experienced changes significantly compared to other section.

As demonstrated in the results, different types of soils produce different pattern of SWCC and hydraulic conductivity. The similarity pattern of SWCCand hydraulic conductivity for silty and gravelly sand are due to the similar types of each soil.The volumetric water content for gravelly and silty sand is at the lower position indicated as coarser material, compare to forest soil which is finer material. Meanwhile, the ability of water to seep in the coarser soil material is higher than finer material.

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