Rainfall Infiltration through Unsaturated Layered Soil Column
(Penyusupan Air Hujan melalui Tanah Tak Tepu pada Tiang Tanah)

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ABSTRACT

Infiltration caused by rainfall will lead to the changes of moisture content and soil pore water pressure or matric suction of the soil. These changes indicate the behavior of the soil especially during wetting and drying process. This paper presents the experimental test result of rain water infiltration into soil column for two samples of soils. The main objectives were to study the effect of rainfall intensity and duration of soil infiltration process for the forest soil and to compare its result to the gravelly sand. Infiltration experimental in this study involved three main components; water supply system, soil column and instrumentations, including percolation collection system. This study uses two types of tensiometers; 5 and 10 cm long. The results of TDR and tensiometers which were used to obtained moisture content and matric suction, respectively, shows that the system was successfully developed. For the forest soil, the result showed that moisture content of the top section is higher compared with the other sections. On the other hand, for gravelly sand, the moisture content in middle section is higher compared with the top and bottom section of the soil. Meanwhile, matric suction for both soils dropped during rainfall and gradually increases towards drying process. Other than that, the comparison of soil matric suction between 5 and 10 cm tensiometers shows significant results for gravelly sand compared to forest soil.

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

ABSTRAK

Penyusupan yang disebabkan oleh hujan akan merubah kandungan lembapan dan tekanan air liang tanah. Perubahan ini adalah merupakan penanda kepada sifat tanah terutamanya semasa proses pembasahan dan pengeringan daripada hujan yang turun. Kertas kerja ini memaparkan keputusan yang dicapai daripada uji kaji makmal berdasarkan ujian air hujan yang menyusup ke dalam dua sampel tanah. Objektif utama kajian ini adalah untuk mengkaji kesan daripada keamatan dan tempoh air hujan untuk sampel tanah dari kampus dan dibandingkan dengan sampel pasir berkerikil. Ujian penyusupan ini terbahagi kepada tiga komponen; sistem bekalan air, tiang tanah dan instrumentasi dan juga sistem pengaliran keluar air. Kajian ini menggunakan dua jenis tensiometer; 5 dan 10 cm panjang. Keputusan yang diperoleh menunjukkan tanah dari kampus mempunyai kandungan lembapan yang tinggi pada bahagian atas tiang dibandingkan dengan bahagian yang lain. Manakala pasir berkerikil pula, tanah pada bahagian tengah tiang menunjukkan kandungan lembapan yang tertinggi. Selain daripada itu, tekanan air liang tanah untuk kedua jenis tanah ini menunjukkan pengurangan semasa hujan, tetapi beransur meningkat semasa proses pengeringan. Selain daripada itu, didapati tekanan air liang antara 5 dan 10 cm tensiometer menunjukkan kesan pada pasir berkerikil berbanding dengan tanah dari kampus.

Kata kunci: Kandungan lembapan; penyusupan; tekanan liang; tiang tanah

INTRODUCTION

Slope failures are commonly caused by soil materials, human activities on slope, rainfall, hillside development and climatic condition such as geological features, topography, vegetation or combination. But for the tropical country that experience high seasonal rainfall, rainfall is believed to be the main reason for slope failures. (Bujang et al. 2006; El-Fadil & Gofar 2008). These rainfall-induced slope failures are due to the loss of matric suction of soils by rainwater (Bujang et al. 2006; Mukhlisin & Taha 2009). Residual soil for tropical country normally composed with the negative pore water pressure above the groundwater table. These residual soils are robustly subjected by climatic and hydrological changes such as precipitation, infiltration, evaporation and transpiration (Rahardjo et al. 2010).

During and after a rainfall event, part of the rainwater that reaches the slope surface infiltrate into the soil while others become the surface runoff. As water infiltrates the slope, matric suction is decreasing as the soil moisture is increasing, subsequently change the structure of soils and lessen the frictional and cohesive strength between particles (Gofar et al. 2006). Consequently, negative pore water pressure between the soil particles and shear strength is decreasing, hence affects the slope stability (Gasmo et al. 2000; Mukhlisin et al. 2011; Mukhlisin & Taha 2012).

This can be concluded that the higher the rainfall intensity, the higher infiltration rate through the soil and hence lower the slopes' factor of safety (Bujang et al. 2006).

Infiltration is the process of water entering soil while infiltration capacity is the maximum rate at which water can infiltrate into the soil. Infiltration rate is the infiltration of water into soil which creates the relationship between rainfall and soil ability to infiltrates. If the infiltration rate exceeds the soil infiltrability, ponding or runoff occurs over the soil surfaces. Researchers believed that the process of infiltration mechanism is complex due to its high nonlinearity of soil water characteristic and soil permeability (Yang et al. 2006).

Other than that, Lee et al. (2011) and Mukhlisin et al. (2006) mentioned that the complexity is due to the parameters such as soil initial moisture condition, soil water retention ability, soil porosity and evaporation rate. Therefore, the needs to study the infiltration mechanisms is essential in order to comprehend the behavior of soil under various rainfall intensity and duration, with the intention that the parameters mentioned can be obtained.

Soil column apparatus is normally used to perform simulated water infiltration into soil. This apparatus has been used extensively to facilitate understanding of rainfall infiltration mechanism. Indrawan et al. (2007) and Yang et al. (2006) explored the effect of rainfall intensity and duration and provide the verification of soil water redistribution and hysteresis phenomenon. Gofar et al. (2008) also conducted the experiment using soil column to investigate the mechanism of rainfall and provide evidence on transient pore water pressure distribution and redistribution of rainfalls.

Even though many researchers have been conducted using soil column for various purposes, the pore water pressures that measured were at the same place or using the same length of tensiometers. In this study, the introduction of difference length of tensiometers inserted into the soil column will measure the difference points of pore water pressure. Therefore, behavior of soil can be further investigated. Moreover, the experimental works of rainfall infiltration behavior into unsaturated soil, on one-dimensional soil column apparatus were examined using the instrumentations, parameters such as moisture content and matric suction. There were two types of tensiometers used in this study; 5 and 10 cm long. Therefore, in this study, the differences of matric suction were determined by the different size of tensiometers.

MATERIAL PROPERTIES

The material used in this study consists of two types of soil. The soil from UKM reserved forest area and gravelly sand that commercially obtained were used for the infiltration experiment. The basic soil properties were investigated such as soil moisture content, bulk density, porosity and water retention ability. The results of the soil properties are summarized in Table 1.

TABLE 1. Basic properties of the soils

	UKM Reserved Forest	Gravelly sand
Moisture content *(%)*	6.69	0.67
Bulk density *(g/)*	1.22	1.72
Porosity *(%)*	0.541	0.349

Other than that, soil water characteristic curve (SWCC) of the soils was obtained through experimental using pressure plate extractor apparatus (PPE). A series of pressure that is in the range from 0 to 15 bar were applied to the samples of soils in the experiments.

EXPERIMENTAL DETAILS

The infiltration test conducted in a soil column apparatus are as shown in Figure 1. The system of the experimental apparatus consists of water supply system, soil column and instrumentations, and percolation collection system.

WATER SUPPLY SYSTEM

Water supply for this experiment was using water flow regulator to simulate rainfall into the column as shown in Figure 1(b). The pump drive used was Masterflex L/S economy, model 07554-80 with variable-speed console by Cole-Parmer. This pump driver which has speed from 1 to 10, was attached with Masterflex L/S Easy –Load II pump heads. L/S tubing was attached to the pump head for water flow. This pump system provides various flow rate depends on the tubing size and speed. For this experiment, tubing size used was L/S 25 which has 4.8 mm internal diameter and can provide 1.7 to 170 mL/min and 10 to 1000 mL/min at 1 to 100 and 6 to 600 rpm, respectively. From the pumping system, water supply was regulated through the pump head and flowing into the soil through the rainfall distributor, hence to the top of the soil. Other than that, filter papers were placed in contact with the soil, thus water can be spread evenly into the soil.

SOIL COLUMN AND INSTRUMENTATIONS

The soil column used in this study consists of the transparent acrylic cylinder, which attached to time-domain reflectometry (TDR) for volumetric water content measurement and tensiometer-transducer system for pore water pressure measurement as shown in Figure 1(a).

SOIL COLUMN

The size of the transparent acrylic cylinder soil column for this experiment is 150 cm high and 20.3 cm diameter. The heights of samples were placed up to 100 cm for both forest soil and gravelly sand. Three threaded holes were drilled at the sides of the column in three layers in order to embedded TDR and tensiometer into the soil.

TIME-DOMAIN-REFLECTOMETRY (TDR)

Volumetric soil moisture in this experiment was measured using time-domain-reflectometry (TDR) probe named time domain reflectometry with intelligent microElements) (TRIME-IT) by IMKO Micro modultechnik Gmbh. TRIME-IT probe consists of two metal rods that used as wave guide for the transmission of the TDR-signal (Figure 1(e)). This probe can also generate high frequency-pulse which propagates along the wave guides generating an electromagnetic field around the TRIME-probe. At the end of the wave guides, the pulse is reflected back to its source. Therefore, the moisture content is calculated inside the TRIME-device. The metal rods attached to the probe were inserted into the soil column through the treaded holes and sealed before rainfall is applied to the column.

TENSIOMETER

Tensiometer is used for measuring volumetric soil water pressure or matric suction. In this study, mini tensiometer used was type T5, from UMS GmbH product. Tensiometer is assembled with several components such as high grade porous ceramic tip, acrylic glass shaft, sensor body and sealed cable as shown in Figure 1(c). The porous ceramic tip is 5 mm in diameter and was filled with degassed water. The porous tip is attached to the acrylic glass shaft, which is also filled with degassed water.

Various lengths are available for the shaft. For these tests, two types of length were used, which are 5 and 10 cm. By using several length of shaft, soil water pressure can be detected in several positions in the column. The shaft of tensiometer is then connected to the sensor body, which has piezoelectric pressure sensor included to measure the soil water tension against atmospheric pressure. This type of tensiometer can detect from 100 kPa to -85 kPa suction or soil water tension. The reading obtained from tensiometer is in hectopascals (hPa).

Tensiometer that was used in the experiment needs to be calibrated before usage. Calibration which is refilling the degassed water into the shaft and sensor body should be bubble –free. Air inside the sensor body through the ceramic tip will influence the soil's conductivity. The lesser air in the tensiometer, the faster respond of tension changes will be detected. On the other hand, more air in the tensiometer will produce no or inaccurate data detected during the experiment. The calibration of the tensiometer should be done for 2 h each.

DATA ACQUISITION

The data from tensiometers and TDR are obtained through separate data acquisition system. For soil moisture, data from TDR is logged through Data loggers globe log from IMKO Micro modul technik Gmbh (Figure 1(d)). This weather proof logger should be supplied for 12V/DC power and data can be atomized transmission via GMS/GPRS if necessary. Data transmitted to the logger can be retrieved using personal computer with the software installed.

For soil water tension, data from tensiometer is obtained through DL6 Data Logger by AT Delta-T Devices Ltd as shown in Figure 1(f). These battery powered logger is equipped with soil moisture sensor, temperature sensor, rain gauge and relay (alarm) channel. Delta LINK software is needed to retrieve data from the logger through personal computer.

In this experiment, soil column was filled with the sample and the soil was compacted in order to simulate the original structure of soil at site. Then TDR and tensiometers are carefully placed inside the column. After TDR and tensiometers have embedded into the soil, silicon sealant was applied at the join between instrument and soil column surface to prevent any leakage during wetting and drying process.

PERCOLATION COLLECTOR SYSTEM

Water percolation collection system is used to measure the discharge of rainwater through percolation. In this experiment, Rainlog Datalogger by Rainwise was used to collect the discharge from soil column (Figure 1(g)). The 8 inches diameter collector tipping bucket will collect 0.01 inch/tip and 0.5 min/tip minimum and maximum, respectively. This battery operated logger fits inside the polypropylene rain gauge and will log total rainfall at a 1 min resolution up for one year duration. For this experiment, rain gauge is set for 0.01 inch/tip.

In this experiment, the discharge of rainwater is measured by rain logger system where data is automatically logged and can be retrieved by personal computers. RL-Loader software is used to configure and download data from the Rainlog. Then, the data is displayed in both text and graphical formats.

It is noted that in order to restraint soil from flowing out into the percolation collection system, the base of the soil column is packed with 20 mm high gravel as a porous material. Then the wire mesh is placed at the bottom of the gravel.

INFILTRATION EXPERIMENTS

A series of infiltration tests were designed to be conducted in the laboratory. Rainfall intensity for all experiments was 1.29e-5 m/s (Table 2) for 1, 3 and 6 h rainfall for each type of soil. Unfortunately, the duration of rainfall for forest soil can only be applied until 5 h due to the ponding condition at the top of soil column.

RESULTS AND DISCUSSION

SOIL WATER CHARACTERISTIC CURVE (SWCC)

The result of SWCC obtained was then fitted with the Van Genuchten (1980) model. The SWCC results for both soils are shown in Figure 2. Based on the result, the SWCC show that the results obtained from laboratory are well fitted with the Van Genuchten (1980) model for both forest soil
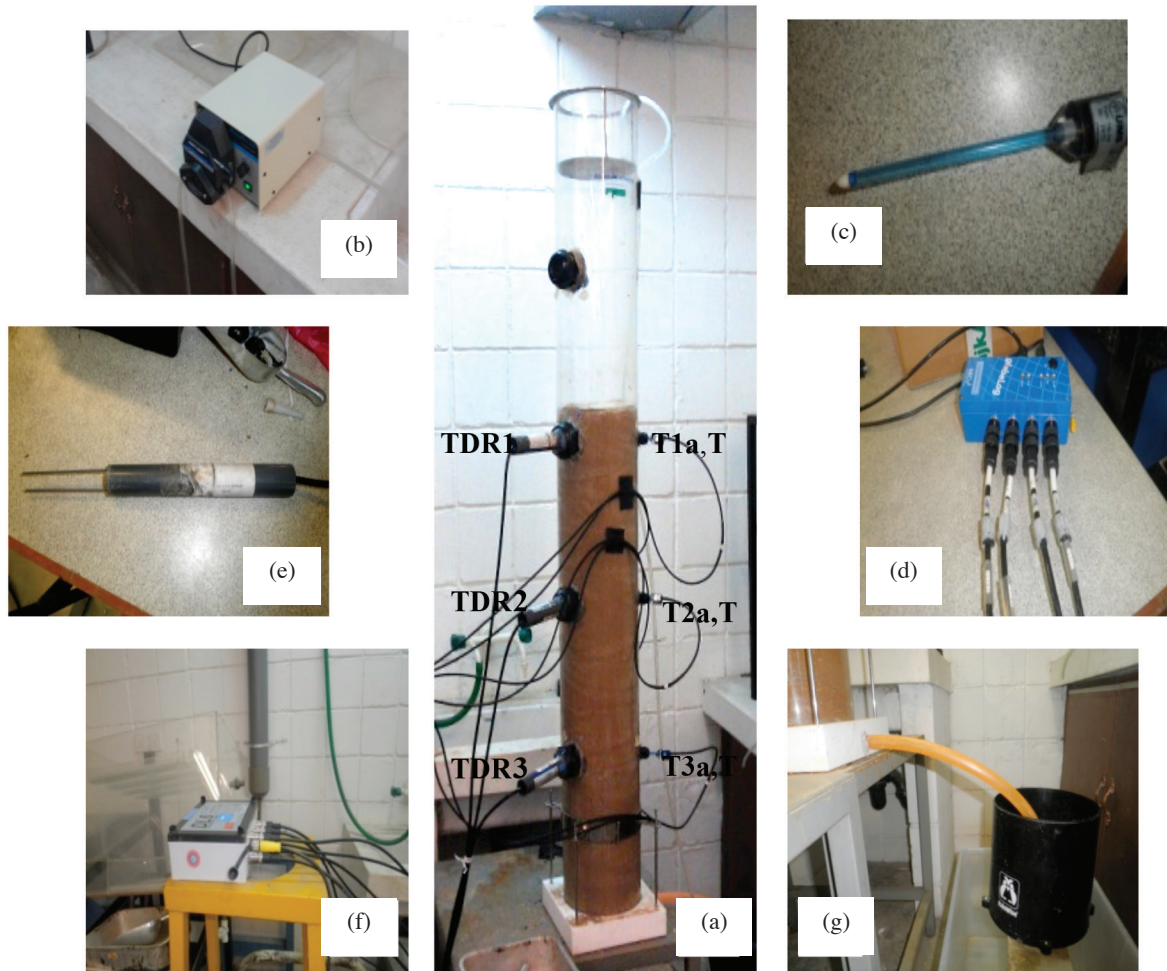
FIGURE 1. Infiltration column apparatus and instrumentations: (a) soil column, (b) flow regulator, (c) tensiometer, (d) data logger for tensiometer, (e) TDR (f) data logger for TDR and (g) rain/discharge logger

TABLE 2. Experimental design for infiltration tests

Sample	Rainfall duration (h)	Drainage duration (h)	Intensity (m/s)
Gravelly sand	1	18.30	1.29e-5
	3	45.00	
	6	72.00	
Forest sample	1	20.30	1.29e-5
	3	94.00	
	5	72.00	

and gravelly sand. Saturated volumetric water content for forest soil is higher than gravelly sand due to the basic soil properties for each soil. The curvatures plotted show that forest soil is higher in water holding capacity than gravelly sand, as well as the residual volumetric water content.

SOIL/WATER PRESSURE OR MATRIC SUCTION

Forest Soil The result for 1 h rainfall shows in Figure 3(a) indicates that during the wetting process, the matric suction at the top and middle section of soil is decreased rapidly. On the other hand, during the drying process, matric suction is higher due to the absorption of water. Other than that, matric suction at the bottom section of column is still in the initial condition during wetting and drying process, because the infiltration of rainwater did not reach the bottom section of the column (Figure 3(d)).

Meanwhile, 3 h rainfall shows that during the wetting process, matric suction is drop rapidly for both top and middle of the column. Other than that, the matric suction increased gradually during the drying process for both top and middle of the column. On the other hand, during
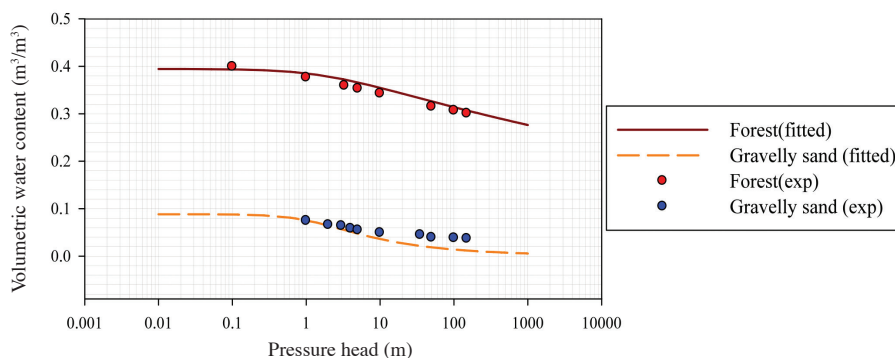
FIGURE 2. Result of SWCC for UKM reserved forest soil and gravelly sand

wetting process, there are only small changes of matric suction captured even though infiltration occurs until the bottom section of the column. This is believed due to the lower position of the column where no evaporation occurs at this section and water retention ability of the soil is low.

For 5 h rainfall shows that for the top and middle section of column, matric suction is dropped rapidly during the wetting process and increased gradually during the drying process. For the bottom section, matric suction increased gradually during the drying process. The result showed that the changes of matric suction during wetting for the bottom section is gradually decreased from the initial reading and cannot be captured at certain times towards the end of the experiment.

Gravelly Sand During the wetting process of rainfall for all durations, the matric suction at all sections of soils is rapidly decreased. On the other hand, the result showed that during the drying process, the matric suction is gradually increased. The results also show that, for all rainfall duration, the matric suction have similar pattern throughout wetting and drying process (Figure 3(f)).

VOLUMETRIC WATER CONTENT SOIL COLUMN

Forest Soil During wetting and drying process for the top section, the result showed that soil moisture for 1 h rainfall is gradually increased. Soil moisture is starting to decrease after 8 h of drying. On the other hand, for 3 h rainfall, soil moisture is starting to decrease after 24 h of drying. Subsequently, soil moisture is starting to decrease after 4 days of drying for 5 h rainfall (Figure 3(c)).

Meanwhile for the middle section, the result showed that soil moisture for the middle section for the column is constant throughout the wetting and drying process. This is due to the position of the soil, where infiltration rate for the forest soil is very low and moisture is trapped in this section.

The bottom section of the column experienced small changes of soil moisture for 1 h wetting and throughout the drying process. But, during 3 h of rainfall, the soil moisture increase rapidly and experience small changes after rainfall and throughout the drying process. There are no changes of soil moisture even though 5 h rainfall is applied to the

column. The position of the lower section is believed to be the reason on the small changes of soil moisture.

Gravelly Sand For gravelly sand, the soil moisture is increased during wetting process and rapidly decreased towards the drying process for all duration of designated rainfall. It shows that the soil moisture for the top section is the lowest, followed by the bottom section. The result also indicated that the highest soil moisture was captured at the middle section of the column. Soil moisture is higher at this section since the rainwater infiltrate and trapped at this section before continue infiltrates to the bottom of the column (Figure 3(g)).

WATER PERCOLATION COLLECTION

Water percolation collection for forest soil is shown in Figure 3(d). From the figure, the result indicates that for 1 h rainfall, the rain water is not infiltrated until the bottom part of the column for the forest soil. Therefore, there is no percolation collection data for 1 h rainfall. For the 3 h rainfall, the result showed that the rain logger started after 45 h rainfall event. This indicates that rainwater took 45 h to infiltrates through the entire column for the forest soil. On the other hand, for gravelly sand, the result showed that infiltration rate is higher than forest soil and infiltrates from top to the bottom of the column in 30 min (Figure 3(h)).

MATRIC SUCTION ON ELEVATION OF SOIL COLUMN

Figure 4 shows the result of matric suction for all tensiometers embedded in the top, middle and bottom of soil column.

Forest Soil Figure 4(a) and 4(b) shows for 1 and 3 h rainfall at t=0 (initial matric suction), both tensiometers were having almost similar reading except the middle section which has slightly different value. During the wetting process, matric suction was decreased which suggest that the soil water suction was slower in the wet soil. As the rainfall stopped, the result showed that the matric suction was increased in which drying process is taking place. The middle section of both types of tensiometer having slightly different value compared to the other sections.
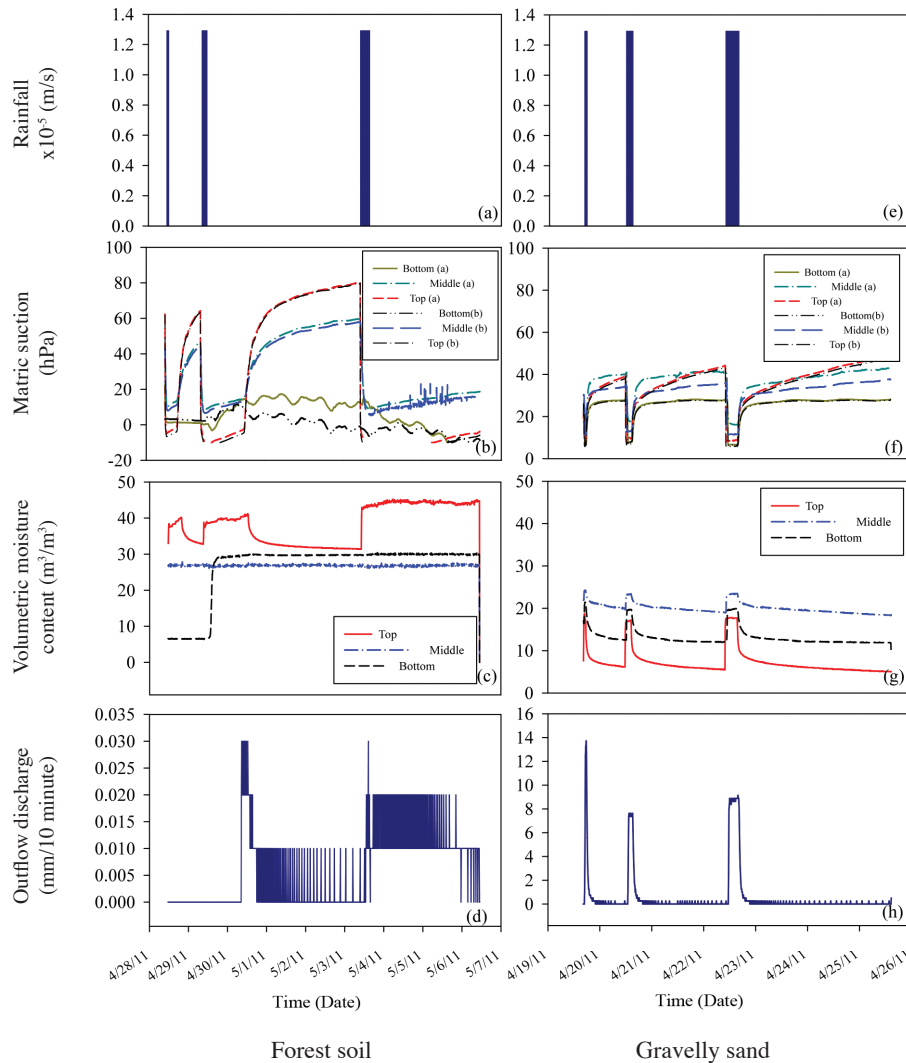
FIGURE 3. Result of the discharge flow rate, matric suction and moisture
content for forest soil and gravelly sand

On the other hand, for 5 h rainfall, during the wetting process, the matric suction is higher than the initial rainfall and the experience increase the value in the drying process (Figure 4(c)). The results showed that the top section of the column has the highest matric suction, followed by the middle and bottom section. It is believed that this event was influenced by the ponding condition that occurs during the experiment. Figure 4(a) shows that the moisture content for the top section for forest soil is highest compare with the other sections, explained the ponding conditions occurrences. Other than that, even though there are slightly different for matric suction of type a and b tensiometer, it shows that the outer part of the column is having higher soil suction than the inner part.

Gravelly Sand Figure 4(d) shows for the 1 h rainfall the initial value of matric suction, t=0 for both type a and b tensiometer have different reading for top and middle part of the column, while almost the same value for the bottom part. During the wetting process until t=1 h, the matric suction for all section started to decrease as soil was wetted. The results showed the increasing of matric suction for all parts due to the drying process, where both types of tensiometers were almost the same value for top and bottom. On the other hand, the value for middle section of column is different for type a and b tensiometer, where type a achieved higher matric suction compared with type b (Figure 4(e) and 4(f)).

Similar to 1 h rainfall, 3 and 6 h rainfall experience the decreasing of soil matric suction while wetting and decreasing during the drying process. Other than that, the matric suction of the middle section of soil column is higher than other sections of the column with value for tensiometer type a is higher than type b (Figure 4(e) and 4(f)).

For the gravelly sand the matric suction for the middle section for both types are dissimilar where type a (5 cm long) tensiometer is higher than type b (10 cm long). These event can be verified through the same condition achieved in Figure 3(b). This event also enlighten that the middle
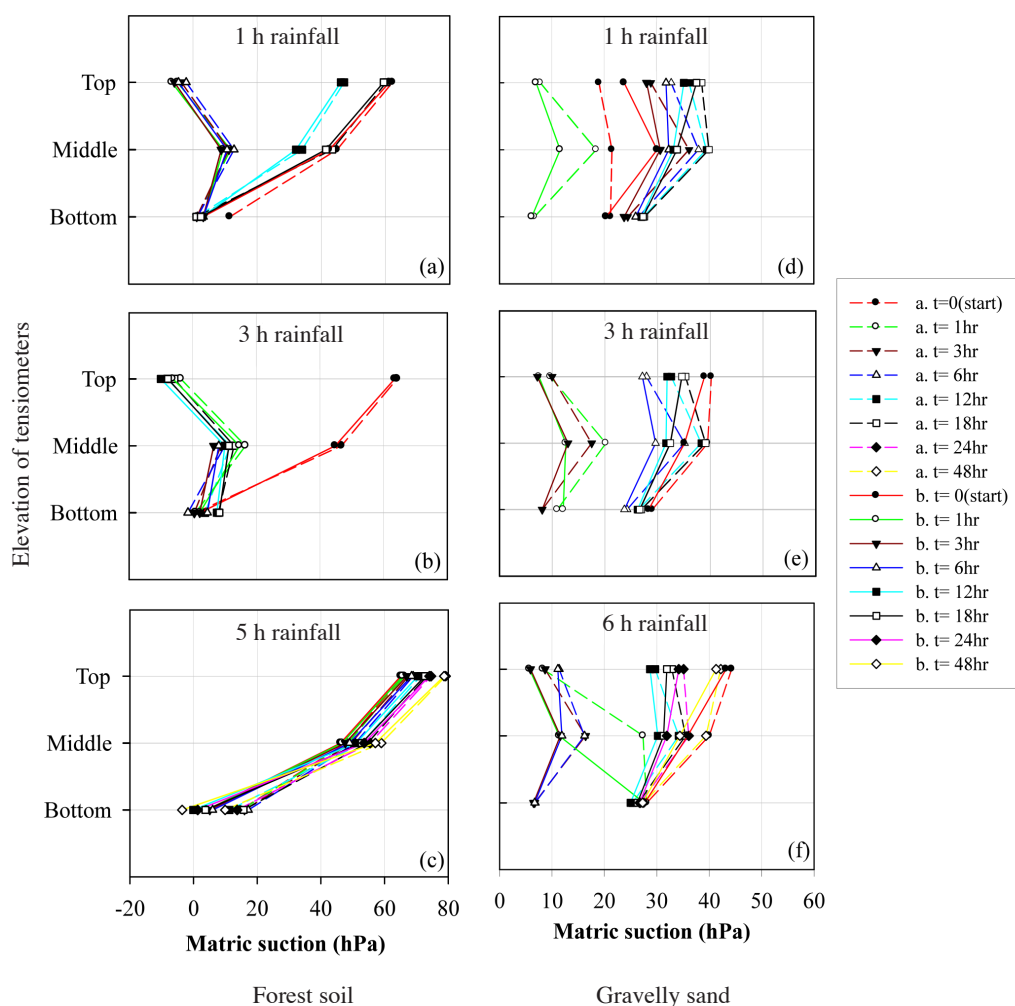
FIGURE 4. Result of matric suction at elevations of soil column for forest soil, and gravelly sand

column is wetter than outer section which means that rainwater infiltrate the middle column and then spread to the outer section of soil.

For all rainfall events, the results obtained for the middle section were higher than the top and bottom section of the column. It is believed that the middle section of the column is the highest soil moisture content compared with other sections, as shown in Figure 3(b). This explained that the result is influenced by the rainwater that infiltrates from the top section and trapped in the column before the water infiltrates to the bottom section. In general, even though the top section of the soil column is covered, the soil surface is prone to dry faster than soil in the middle. On the other hand, water from the bottom section will percolate downward and discharged. Consequently, these will increase the drying process as rainwater has its path for drainage.

CONCLUSION

A series of infiltration tests were conducted to study the pattern of soil moisture and pore water pressure in soil column under designated simulated rainfall. The rainwater is applied into the soil and percolate through the soil column and then, the discharge of percolation is measured by rain logger.

The result showed that the infiltration rate of the forest soil is lower than gravelly sand. It is believed due to the infiltrability coefficient of the soil whereby gravelly sand is higher than the forest soil. SWCC result showed that water retention ability is higher for the forest soil than the gravelly sand. Pore water pressure for both soils are having similar pattern where the pore water pressure is decreased rapidly during rainfall is applied to the soil and gradually increased subsequently. But for the forest soil, due to the low infiltrability, the bottom part of the soil only shows small changes of pore water pressure.

Other than that, soil moisture content of both soils shows similar pattern where the soil moisture is increased rapidly during rainfall and gradually decreased subsequently. But for the forest soil, soil moisture for the middle part experienced small changes due to its position and low infiltrability rate, where rainwater is trapped in between the soil particle. Using different length of

tensiometer to measure matric suction shows that the outer part of soil column experience higher matric suction compared with the inner part. This shows that the outer part of the soil column is dryer than the inner part. It is believed that the rain water infiltrates and percolates downward to the inner part first and then gradually moves to the outer part of the column.

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