Jurnal Teknologi

Full Paper

RESPONSE OF SUCTION DISTRIBUTION DUE TO VARIATIONS OF PERMEABILITY IN RESIDUAL SOIL SLOPE

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Article history
Received
18 January 2016
Received in revised form
8 March 2016
Accepted
18 March 2016

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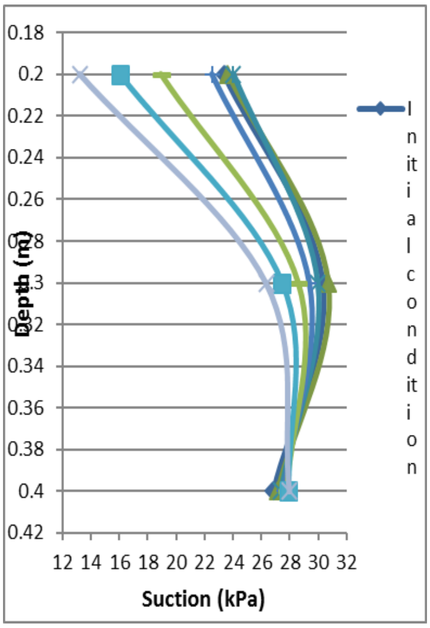
Graphical abstract



Abstract

A landslide in residual soil normally occurs immediately after heavy rainfall. Previous studies have shown that decrease in matric suction during rainfall decreases the shear strength of soil and results in landslides. One of the factors that contribute to infiltration of water into soil is permeability of the soil which varies with depth. The variations of permeability can either prevent or allow water to infiltrate into deeper soil layer. Therefore, the aim of this study is to determine the suction distribution in a two- layered residual soil system with variable permeability function using laboratory physical slope model. The K_{sat} for Grade V varies from 5.11 x 10^{-4} m/s for relict joint of 100 mm spacing to 5.40 x 10^{-5} m/s for relict joint of 300 mm spacing. Meanwhile the K_{sat} for Grade VI represent Grade VI without burrow holes, 5.00 x 10^{-7} m/s and K_{sat} with burrow holes, 6.98 x 10^{-4} m/s. The infiltration tests were conducted for 12 series of experimental program. The suction distribution due to variations of permeability and rainfall intensity were determined. The results illustrated that suction distribution responded in various ways depending on permeability of the layered soil and also the rainfall intensity.

Keywords: Suction distribution, residual soil, permeability, rainfall intensity

Abstrak

Kejadian tanah runtuh di tanah baki biasanya berlaku selepas hujan lebat. Hasil kajian yang dilakukan oleh penyelidik sebelum ini, merumuskan bahawa sedutan matriks berkurangan semasa hujan, dengan itu mengurangkan kekuatan ricih tanah dan menyebabkan tanah runtuh berlaku. Salah satu faktor yang menyumbang kepada penyusupan air ke dalam tanah adalah kebolehtelapan. Di samping itu, kebolehtelapan tanah baki adalah berbeza dengan kedalaman. Variasi kebolehtelapan ini mencegah atau membenarkan air untuk menyusup masuk ke dalam lapisan yang lebih dalam. Oleh itu, tujuan kajian ini adalah untuk mengenal pasti taburan sedutan bagi dua lapisan sistem tanah baki dengan ciri-ciri kebolehtelapan yang berbeza pada bahagian atas dan bawah. Nilai K_{sat} bagi Gred V berubah dari 5.11 x 10^{-4} m/s bagi kekar dengan jarak100 mm hingga 5.40 x 10^{-5} m/s bagi kekar dengan jarak 300 mm. Sementara itu, nilai K_{sat} bagi Gred VI mewakili nilai Gred VI tanpa lubang sarang , 5.00 x 10^{-7} m/s dan K_{sat} dengan lubang sarang, 6.98 x 10^{-4} m/s. Ujian penyusupan telah diadakan untuk 12 siri program eksperimen. Variasi kebolehtelapan dan juga taburan hujan telah dilakukan untuk memantau taburan sedutan dalam kedua-dua lapisan tanah. Keputusan menggambarkan bahawa taburan sedutan bertindak balas dalam pelbagai cara berdasarkan lapisan kebolehtelapan dan juga taburan hujan.

Kata kunci: Taburan sedutan, tanah baki, kebolehtelapan, taburan hujan

1.0 INTRODUCTION

Rainfall-induced slope failure are common problems in many tropical area covered by residual soil. Although, many factors contribute to this type of failure, they can however be classified into intrinsic and external factors. The main intrinsic factor is hydraulic conductivity properties of the soil or saturated coefficient of permeability (k_{sat}). While the external factors mainly refer to climatic condition such as rainfall intensity and duration.

Weathering process resulted in decomposition of rock to grade VI (lateritic layer) and grade V (saprolitic layer) which is often referred to residual soil. Hence, residual soil properties varies with depth [1]. In addition, many activities such as root plant, soil fauna, burrow hole, etc. occur within the grade VI soil layer and increases the permeability in this layer [2–4]. However, the grade V soil layer is characterized with the existence of relict structures which also increases the permeability of this soil layer [5]. Therefore, these factors contribute to discrepancy in permeability and hence suction distribution between the two soil layers.

Previous studies such as [5–9] have discussed on suction distribution in a two-layered residual soil and concluded that capillary barrier effect exist between upper and lower soil layers. However, from the previous studies, the combined effect of factors that affect permeability in grade V and grade VI as outlined before and the corresponding suction distribution in both layers are yet to be explored. Therefore, the aim of this study is to determine the suction distribution in a two-layered soil system with variable permeability properties due to the effect of factors described above. The study was conducted through laboratory experimental approach using laboratory physical slope model. The selected soil samples were prepared in the slope model and subjected to various rainfall patterns through a rainfall simulator. The corresponding suction distributions were monitored through a data logger which is part of the laboratory set up.

2.0 METHODOLOGY

The study commenced with identification of soil properties for the two-layered soil system. Soil sample was sourced from Balai Cerapan, UTM, Skudai. Previous study performed in this area had concluded that the area is covered by residual soil that have different soil profiles with depth [10].

The physical modelling or infiltration test was conducted using infiltration model, rainfall simulator, measuring sensors and data logging and acquisition system. The Infiltration model was 1000 mm in length, 300 mm in width and 800 mm in height. The frame of the model was made of stainless steel and the sidewalls were made from acrylic sheet of 5 mm thickness. As shown in Figure 1, the acrylic sheet allows visual observation of water movement in the layered soil during infiltration tests. Three types of boundary condition were applied to the infiltration model, i.e. zero-flux boundary at both side walls, a unit hydraulic gradient flow at bottom of the model and at toe of the slope, while an outlet was located at the top of the model to create no-ponding upper flux boundary during testing.

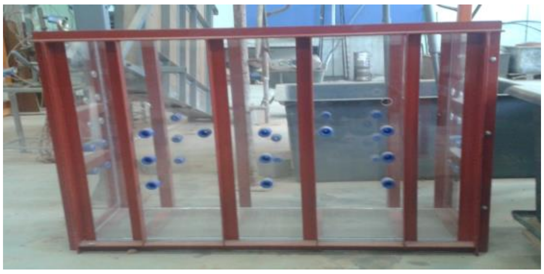


Figure 1 Infiltration model box

The rainfall simulator consists of rainfall simulator frame and outlet valves. The frame was 1200 mm in both length and width with adjustable height. Parts of the rainfall simulator set up are water tank and motor. The water tank supply water to the rainfall simulator while the motor swings the outlet valve to distribute the simulated rainfall equally to the entire area of the infiltration model. The rainfall intensity used in this study was determined from the recorded field data. As suggested by [11], about 70% of the total rainfall was applied as infiltration, while the remaining 30% is assumed to be surface runoff. The initial suction condition was assumed to be the suction value corresponding to the residual water content from the soil SWCC [10]. Two main data, i.e., suction distribution and run off data were recorded during the infiltration test.

Tensiometers and runoff collector were used as instrumentation during the infiltration tests. The tensiometers were connected to the pressure transducer and from the transducer to the data logger for automated data recording. The purpose of the pressure transducer is to convert the data from Ohm to kPa. Table 1 shows the experimental program used in this study.

Table 1 Experimental program

Exp. No	Soil Configuration	Slope Angle (°)	Rainfall Intensity (m/s)	Time
1a	Sandy silt underlain by silty gravel with RJ spacing of 100 mm	18	1.7196×10^{-5}	1 hour
1b	Sandy silt underlain by silty gravel with RJ spacing of 100 mm	18	1.7694×10^{-6}	24 hours
1c	Sandy silt underlain by silty gravel with RJ spacing of 100 mm	18	4.260×10^{-7}	7 days
1d	Sandy silt underlain by silty Gravel with burrow hole and RJ spacing of 100 mm	18	1.7196×10^{-5}	1 hour
1e	Sandy silt underlain by silty Gravel with burrow	18	1.7694×10^{-6}	24 hours

	hole and RJ spacing of 100 mm			
1f	Sandy silt underlain by silty Gravel with burrow hole and RJ spacing of 100 mm	18	4.260 x 10^{-7}	7 days
2a	Sandy silt underlain by silty gravel (RJ spacing 300 mm)	18	1.7196 x 10^{-5}	1 hour
2b	Sandy silt underlain by silty gravel with RJ spacing of 300 mm	18	1.7694 x 10^{-6}	24 hours
2c	Sandy silt underlain by silty gravel with RJ spacing of 300 mm	18	4.260 x 10^{-7}	7 days
2d	Sandy silt underlain by silty Gravel with burrow holes and RJ spacing of 300 mm	18	1.7196 x 10^{-5}	1 hour
2e	Sandy silt underlain by silty Gravel with burrow holes and RJ spacing of 300 mm	18	1.7694 x 10^{-6}	24 hours

RJ – Relict joint

The permeability values (k_{sat}) for Grade V and Grade VI soil used in this study are tabulated in Table 2. The permeability value for each layer is determined using modified permeability test conducted in the laboratory and a maximum and minimum value was selected for this study. The infiltration tests were performed on 18° slope inclination because the slope angle is not the main parameter tested in this study.

Table 2 Permeability properties for each layer

Soil layer	Saturated permeability, k_{sat} (m/s)
Silty gravel (grade V)	
Relict joint of 100 mm spacing	5.11 x 10^{-4}
Relict joint of 300 mm spacing	5.40 x 10^{-5}
Sandy silt (Grade VI)	
Without burrow holes	5.00 x 10^{-7}
With burrow holes	6.98 x 10^{-4}

3.0 RESULTS & DISCUSSION

The properties of Grade V and Grade VI soil of Balai Cerapan are shown in Table 3. These properties are in good agreement with those obtained by previous researchers such as [12–14].

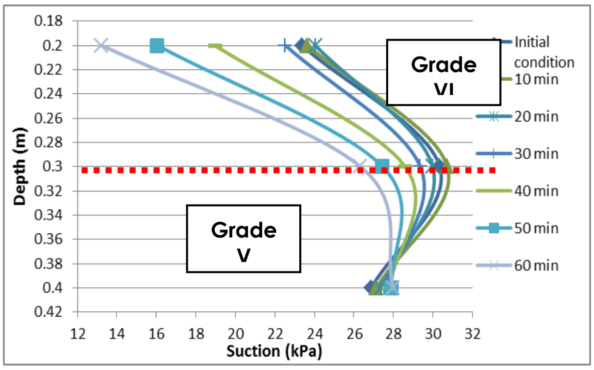
Table 3 Properties of Grade V and Grade VI residual soil

Composition	Grade V	Grade VI
Gravel (%)	48	0
Sand (%)	15	33
Silt (%)	20	34
Clay (%)	17	33
Liquid Limit (%)	53.2	59.3
Plastic limit (%)	35.5	31.9
Plasticity index	17.7	27.4
Moisture content (%)	32	32
Specific Gravity, G_s	2.63	2.65
Bulk Density (kg/m³)	1805	1415
Dry Density (kg/m³)	1366	1080
k_{sat} (m/s)	3.68 x 10^{-6}	5.0 x 10^{-7}

The results of the infiltration tests performed in this study are presented in following sub-sections. Firstly, the results explained the suction distribution due to 1-hour rainfall intensity for all layers, and then followed by suction distribution due to 24-hour rainfall intensity and finally the suction distribution due to 7-day rainfall intensity. Only suction distribution measured at the middle of the slope model were presented because the suction measured at other positions (i.e. the crest and toe) of the slope model were almost identical to each other. Finally, the effect of variation of permeability on suction distribution was also presented and discussed in this section.

3.1 Suction Distribution due to 1-hour Rainfall intensity

Figures 2 and 3 illustrate the suction distribution in a two-layered soil profile with relict joints in Grade V soil layer. The relict joints are of 100 mm and 300 mm spacing, respectively.



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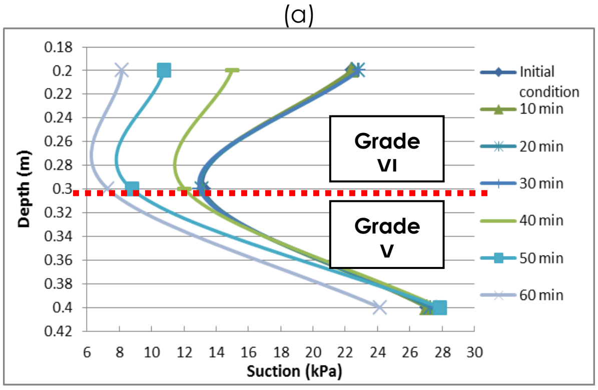

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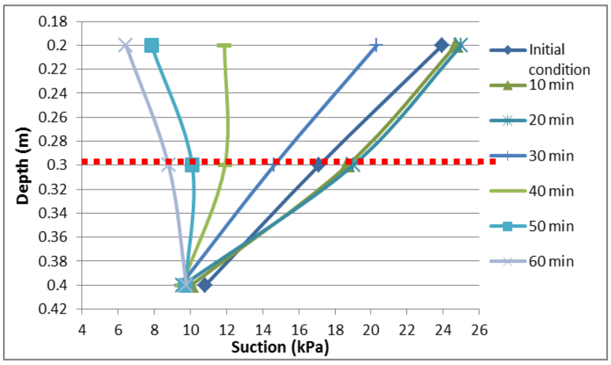
Figure 2 Suction distribution due to 1-hour rainfall in a two-layered soil with relict joint of 100 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole

The Suction distribution in the Grade VI soil layer without any burrow holes shows similar trend of suction distribution for both 100 mm and 300 mm relict joint spacing. The variation in the suction distribution occurred at the upper grade VI soil layer and at the interface of the two soil layers. However, the suction remained unchanged in the grade V soil layer. A significant variation in suction distribution is observed due to relict joint spacing. The variation due to 300 mm relict joint spacing was higher than that of 100 mm relict joint spacing. For 100 mm relict joint spacing, the suction in the grade VI residual soil layer changes from 24 kPa at the beginning of the rainfall infiltration to 13.23 kPa at the end of 1-hour rainfall. However, for the 300 mm relict joint spacing, the suction changes from 24 kPa at the beginning of rainfall to 6.4 kPa after 1-hour rainfall. Similarly, at the interface of the two soil layers, the suction changes from 30 kPa to 26.33 kPa and from 17.13 kPa to 8.8 kPa for 100 mm and 300 mm relict joint spacing, respectively. These variations in the suction distribution clearly shows that 100 mm relict joint spacing without burrow hole in the grade VI soil layer hold more water compared to 300 mm relict joint spacing without burrow hole. This may be attributed to the difference in permeability when a burrow holes are considered. The permeability is higher for 100 mm spacing (i.e. about 3 orders of magnitude) compared to 300 mm spacing (which is about 2 orders of magnitude).



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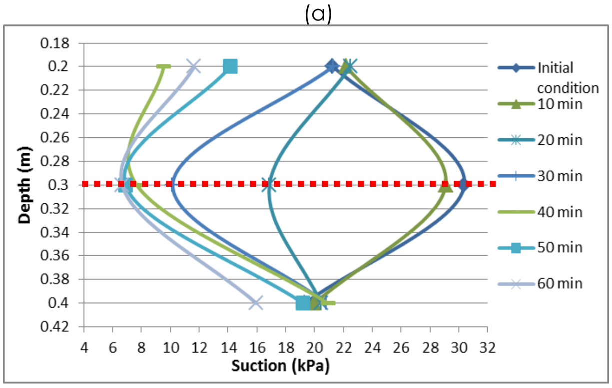


(b)

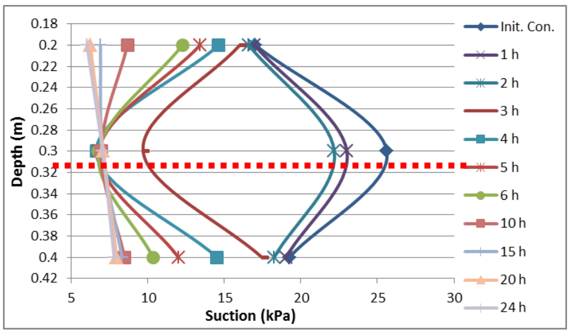
Figure 3 Suction distribution due to 1-hour rainfall in a two-layered soil with relict joint of 300 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole

With burrow hole been considered, the breakthrough (i.e. infiltration of water into the lower grade V soil layer) occurred at 60 minutes for 100 mm relict joint spacing. However, it occurred at 50 minutes for 300 mm relict joint spacing. At early stage of testing the suction distribution remained unchanged for about 40 minutes for 100 mm relict joint spacing while for 300 mm relict joint spacing, the suction responded to the infiltration about 10 minutes from the beginning of the experiment. The suction recorded at the end of 1 hour rainfall duration is about 5 kPa for both cases. This shows that the top layer almost achieved full saturation condition at the end of testing period (i.e. 1 hour). This may be because of the existence of burrow hole which holds the water in the upper layer as shown in Figure 4. At the end of testing period, the soil was carefully excavated to investigate the water flow in the soil. The visual observation shows that the water filled up the holes.

Figure 4 Infiltrating water hold in the burrow hole

3.2 Suction Distribution Due to 24-hour Rainfall intensity

Figures 5 and 6 show suction distribution for the 24-hour infiltration test.



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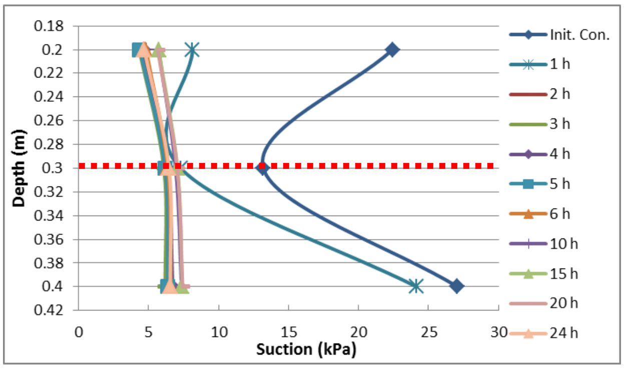

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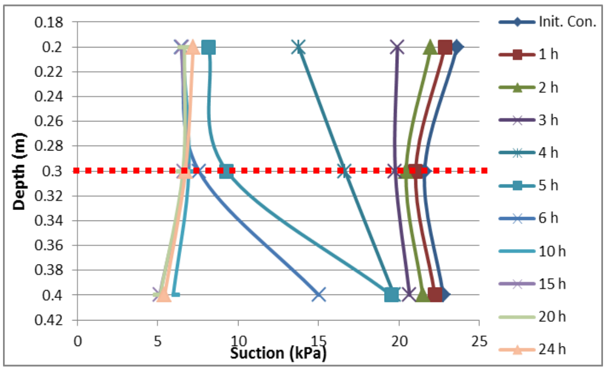
Figure 5 Suction distribution due to 24-hour rainfall in a two-layered soil with relict joint of 100 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole



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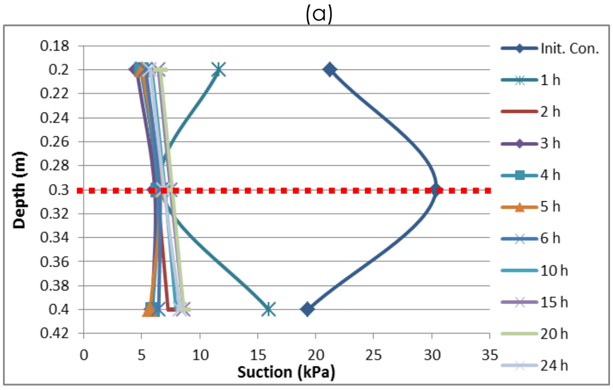


(b)

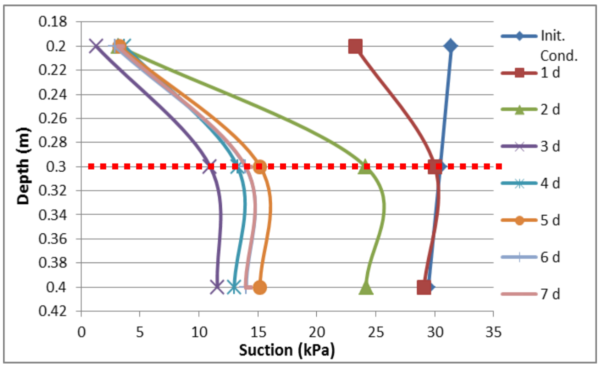
Figure 6 Suction distribution due to 24-hour rainfall in a two-layered soil with relict joint of 300 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole

The suction distribution due to 24-hour rainfall shows that the soil profile attained a unit gradient condition in all cases. However, this condition is attained at different time depending on the relict joint spacing and burrow hole condition. For the experimental program without burrow hole in the Grade VI soil layer, the difference in permeability is about 3 and 2 orders of magnitude for 100 mm and 300 mm relict joint spacing, respectively. Therefore, it takes about 600 minutes to attain a unit gradient condition. However, when burrow holes are considered, the soil attained a unit gradient condition at 120 minutes. Therefore, it can be concluded that the higher the difference in permeability between the two soil layers the longer it takes to attain a unit gradient condition.

Furthermore, for the experimental program without burrow hole, the suction decreases slowly especially for 100 mm relict joint spacing compared to 300 mm relict joint spacing. For 100 mm relict joint spacing, the suction in the upper grade VI soil layer, responded to the infiltration at about 240 minutes whereas it responded to infiltration at about 60 minutes for 300 mm relict joint spacing. At the interface of the two soil layers, the suction responded to the infiltration and decreases at about 60 minutes of rainfall infiltration in both cases. In contrast, for the experimental program with burrow hole, a distinct variation in suction distribution occurred at about 60 minutes in the upper grade VI soil layer and at the interface of the two soil layers. However, a slight changes were observed in the lower grade V soil layer (i.e. less than 5 kPa for both cases). At the end of testing period, a unit gradient condition was observed in both cases and the suction varies between 10 kPa to 5 kPa.

3.3 Suction Distribution Due to 7-day Rainfall intensity

Figures 7 and 8 illustrate the suction distribution for 7-day infiltration tests.



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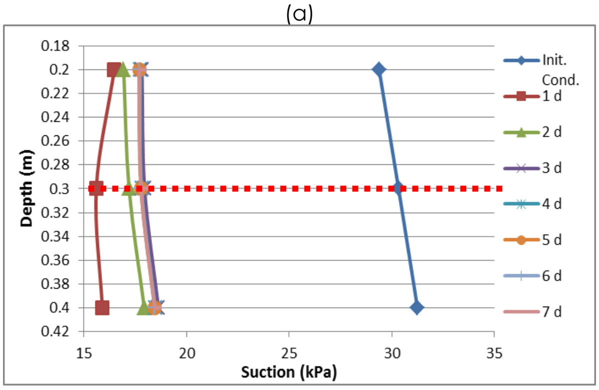
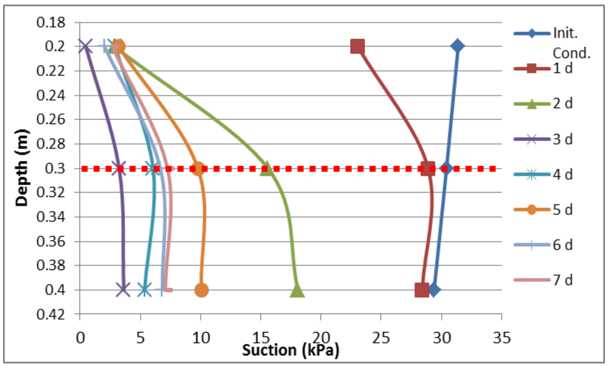


(b)

Figure 7 Suction distribution due to 7-day rainfall in a two-layered soil with relict joint of 100 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole

For cases without burrow hole, the suction dropped at 1 day in the upper grade VI soil layer. As infiltration continues, the suction decreases continuously up to the 4th day. However, the suction observed in the 4th day is similar to that of the 2nd day. It then remained unchanged until end of testing period. This phenomena observed, is referred to suction redistribution. At the interface of the two soil layers and lower grade V soil layer more chaotic conditions were observed compared to the upper grade VI soil layer. For 100 mm relict joint spacing, the suction distribution observed in 1 day, was similar to that of initial condition. However, it decreases slightly for 300 mm relict joint spacing. Similarly, for 100 mm relict joint spacing, the suction decreases continuously for the 2nd and 3rd day and later in increases in the 4th and 5th day. A unit gradient condition was attained in the 6th day for the 100 mm relict joint spacing. However, the suction slightly increases in the 7th day for 300 mm relict joint spacing. This chaotic condition occurred due to differences in permeability function in both soil layers. Therefore, the infiltrating water required more time before it infiltrates the lower grade V soil layer. This causes the suction to increase and decrease before a unit gradient condition is achieved. This situation is a common factor that contribute to slope failure and it occurs due to heterogeneity in residual soil [15].



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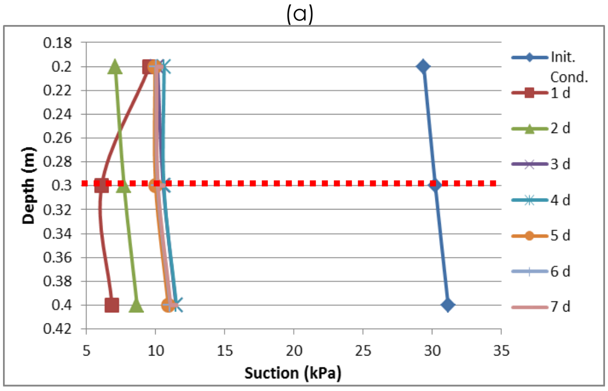

(b)

Figure 8 Suction distribution due to 7-day rainfall in a two-layered soil with relict joint of 300 mm spacing in Grade V soil (a) Grade VI without burrow hole (b) Grade VI with burrow hole

For cases with burrow hole, the redistribution of suction is more stable than without burrow hole. After 1 day of infiltration, the suction drops drastically. However, it starts to increase in the 2nd day before it decreases again in 3rd day and reaches a unit gradient condition.

In addition, in the grade VI soil layer without burrow hole the suction almost reached 0 kPa. This implies that the infiltrating water is retained in this soil layer and resulted in full saturation of the layer in the 3rd day. However, in the grade VI soil layer with burrow hole, the minimum suction observed is 17 kPa and 6.7 kPa for 100 mm and 300 mm relict joint spacing, respectively. This situation implies that, the grade VI layer without burrow hole retained more water compared to the grade VI soil layer with burrow hole. The infiltrating water easily flows into the lower grade V soil layer for the experimental program with burrow hole.

4.0 CONCLUSIONS

The permeability is one of the main factors that contribute to suction distribution in two layered soil profile. The conclusions that can be drawn from this study include:

a. In the case of 1-hour rainfall intensity, the capillary barrier effect is more effective in experimental program without burrow hole. This is because the difference in the soil permeability is higher in the experimental program without burrow than experimental program with burrow hole.
b. For the 24-hour rainfall intensity, the water infiltrates into the lower grade V soil layer easily for the experimental program with burrow hole. However, it takes some time before it percolates (breakthrough) the lower grade V soil layer for the experimental program without burrow hole.
c. For the 7-day rainfall intensity, a chaotic condition in both experimental programs was observed. However, experimental program with burrow hole demonstrate more chaotic condition than experimental program without burrow hole.
d. The effectiveness of capillary barrier effect due to arrangement of grades V and VI soil layers is more pronounced when the difference in the permeability function between the two layers is more than 2 orders of magnitude.

Acknowledgement

This work was supported by a research grant from the RUG of UTM (Tier 1) (Q.J130000.2522.11H04)

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