Malaysian Journal of Civil Engineering 27 Special Issue (1):34-56 (2015)

EFFECT OF FINE-GRAINED SOIL LAYER THICKNESS ON THE PERFORMANCE OF MODIFIED CAPILLARY BARRIER SYSTEM

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Abstract: Slope instability due to rainfall infiltration constitutes major natural disasters in many tropical countries covered by residual soil. In these types of soils, groundwater table usually exist at considerable depth with significance thickness of unsaturated soil above water table. Negative pore water pressure or matric suction exist in the unsaturated soils and contributes additional shear strength to the soil. However, the matric suction reduces due to rainfall infiltration and invariably reduces the additional shear strength provided by the matric suction. The principle of capillary barrier is amongst the methods employed to reduce infiltration of rainfall into unsaturated soil and the infiltrating water into the system is stored in the upper (fine-grained) soil layer. Therefore, this paper highlights the effect of different thickness of fine-grained soil layer on performance of a modified capillary barrier system using numerical modelling approach. The capillary barrier was constructed from residual soils and subjected to three different rainfall intensities of 1 hour, 24 hour and 7 day. The thickness of fine-grained soil layer was varied from 0.1 m to 0.3 m while the coarse-grained soil layer and the unsaturated drainage layer were maintained as 0.3 m and 0.1 m respectively. The results shows that 0.3 m thick fine-grained soil layer is more effective in preventing breakthrough occurrence in case of capillary barrier without unsaturated drainage layer. However, when the capillary barrier was modified with gravel as unsaturated drainage layer, 0.1 m thick fine-grained soil layer was sufficient to prevent breakthrough occurrence for 1 hour and 24 hour rainfall intensities. In the case of 7 day rainfall intensity, breakthrough occurred after 4th day of rainfall infiltration in all the varied thicknesses of the fine-grained soil layer. Therefore modified capillary barrier with unsaturated drainage layer enhance the performance of capillary barrier system by transporting the infiltrating water before breakthrough occurrence. Similarly, it helps in reducing the thickness of fine-grained soil layer.

Keywords: *Capillary barrier, unsaturated drainage layer, fine-grained layer, breakthrough*

1.0 Introduction

The shear strength of soil is an important parameter required in many geotechnical analyses where stability is required such as stability assessment of slopes. Unsaturated residual soil slopes are generally characterized with deep groundwater table and a substantial thickness of unsaturated soils above water table. In these unsaturated residual soil, negative pore water pressure or matric suction exist which contributes additional shear strength to the soil. The matric suction decreases due to rainfall infiltration into the unsaturated residual soil slope and the apparent shear strength provided by the matric suction disappears or reduces significantly enough to trigger slope failure (Fredlund and Rahardjo, 1993; Md.Noor, 2011; Rahardjo *et al*., 2014; Rahardjo *et al*., 2000).

To preserve matric suction in the unsaturaetd soil, several methods including the horizontal drains (Rahardjo *et al*., 2003; Rahardjo and Leong, 2002; Sontoso *et al*., 2009); system with capillary barrier effect (Krisdani *et al*., 2005; Rahardjo *et al*., 2013); geotextile (Ahn *et al*., 2002) have been investigated as preventive measures against rainfall infiltration into unsaturated soil slope. Among these preventive measures capillary barrier is considered as the most effective method of preventing loss of matric suction due to rainfall infiltration (Li *et al*., 2013; Rahardjo *et al*., 2012).

A capillary barrier is a soil system that consists of unsaturated fine-grained soil layer overlying unsaturated coarse-grained soil layer (Ross, 1990; Stormont, 1996). It works on the basis of particle size contrast in the two soil layers and a capillary break which develops at the interface of the two soil layers. This contrast in particle sizes results in contrast in unsaturated hydraulic properties of the two soil layers and forms hydraulic impedance that limits downward water movement (Khire *et al*., 2000). The infiltrating water into a capillary barrier system is temporarily stored in fine-grained soil layer by capillary forces and is ultimately removed by evaporation, evapotranspiration or by lateral drainage. A system with capillary barrier effect is normally designed to ensure that it can store the infiltrating water from rainfall until it is subsequently removed through either natural processes such as evaporation or by the used of unsaturated drainage layer above the interface of the two soil layers when the system is sloped (Li *et al*., 2013; Morris and Stormont, 1997; Stormont and Anderson, 1999). The principal variable for design of a capillary barrier system is the thickness of fine-grained soil layer because it holds the infiltrating water by capillary forces.

A capillary barrier system is found to be less effective when the initial soil suction is low especially during wet period and one of the method of improving the performance of capillary barrier is by modifying it with inclusion of unsaturated drainage layer above the interface of the two soil layers (Stormont and Morris, 1997). An unsaturated drainage layer is sloped soil layer of high permeable material placed above the interface of the two soil layers. It is usually constructed with materials of high permeability than the two soil layers and its inclusion allow original soil material to be used as fine-grained soil layer (Stormont and Morris, 1997).

Therefore this paper is aimed at demonstrating the role of unsaturated drainage layer in reducing the thickness of fine-grained soil layer in a modified capillary barrier system constructed from residual soil and gravel. The study commenced by determining the basic material properties and then a finite element commercial software (Seep/W) was employed in the numerical simulation works with the basic material properties as input parameters. Different thickness of fine-grained soil layeres were varied in the seepage model and corresponding pore water pressure distributions were determined and analyzed. However, prior to the actual seepage analyses several other analyses were conducted to simulate the actual soil condition before any rainfall event.

2.0 Materials and Methods

Tropical residual soil and gravel were used in this study. The tropical residual soil which mainly consists of materials dominantly decomposed to Grade VI and Grade V of saprolitic soils were obtained from Balai Cerapan sloping site within the campus of Universiti Teknologi Malaysia, Johor Bahru. These soils were classified as sandy silt and silty gravel respectively. Typical profile of these soils arrangement as obtained from site investigation work in the area is presented in Figure 1. From the soil profile the Grade VI (sandy silt) soil exist above the grade V (silty gravel) soil. The gravel material used as unsaturated drainage layer is a crushed granite obtained commercially. The particle size distribution of these materials are presented in Figure 2. The classification and other properties tests such as the moisture content, liquid limit, plastic limit, plasticity index and the specific gravity were conducted using standard procedure outlined in BS 1377 Part 2: 1990 (BSI, 1990). The permeability tests for residual soils and gravel were performed using falling head and constant head permeability methods in accordance with BS 1377: Part 5:1990. Table 1 summarizes the properties of the materials used in this study.

The soil water characteristics curve (SWCC) which shows the relationship between the matric suction and the volumetric water content of materials were determined from pressure plate test in accordance with the standard procedure outlined in ASTM D6836-02 (ASTM, 2008). Axis translation technique was adopted whereby the air pressure (u_a) inside the apparatus was increased while the pressure of the water phase (u_w) was maintained at atmospheric level (Simms and Yanful, 2004). The SWCC of the materials are presented in Figure 3.

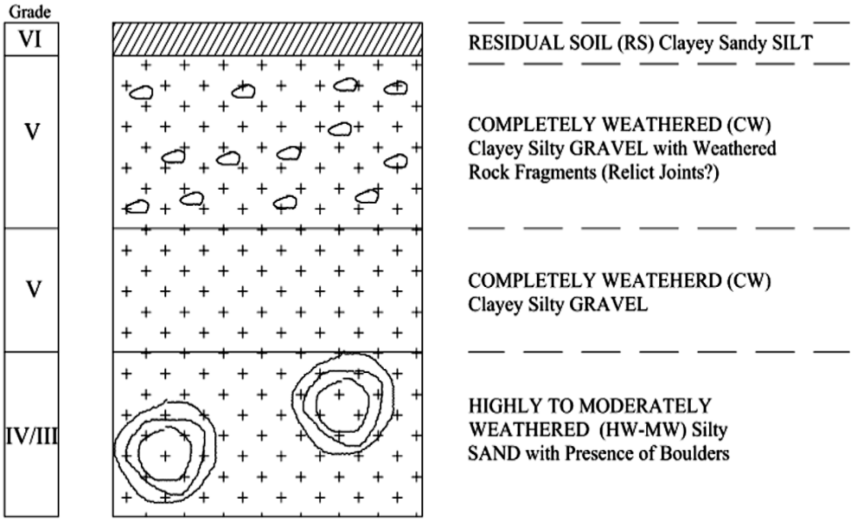

Figure 1: Typical soil arrangements in Balai Cerapan Slope

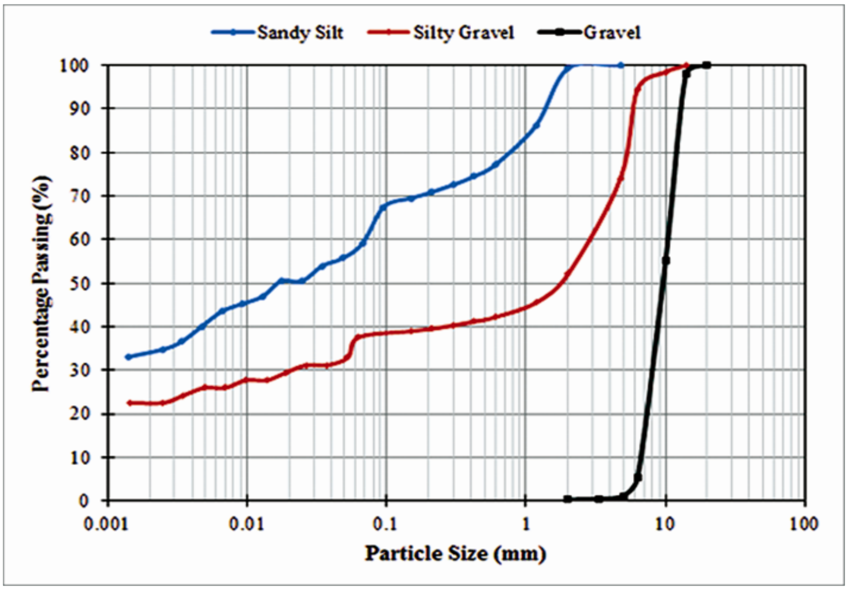

Figure 2: Particle size distribution of the materials

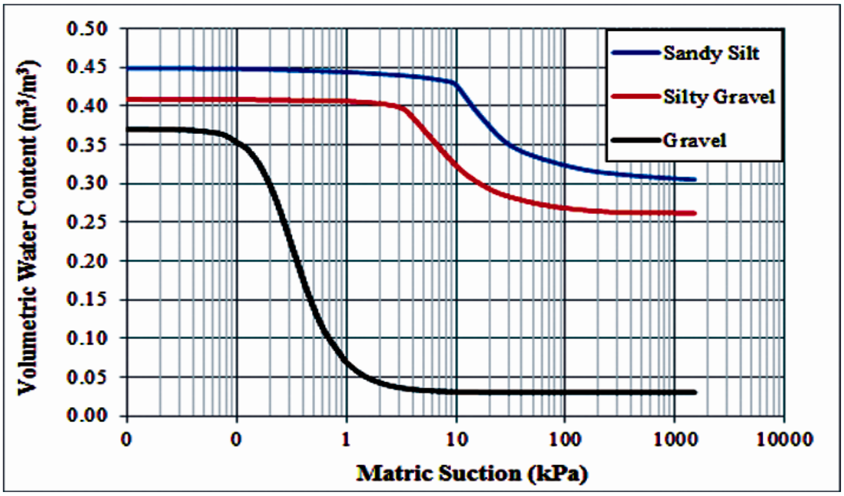

Figure 3: Soil water characteristics curves of the materials

Table 1: Material properties used in the study

Description	Unit	Sandy Silt	Silty Gravel	Gravel
British Soil Classification system	-	MHS	GMH	SP
Composition				
Gravel	%	0	48	100
Sand	%	33	15	0
Silt	%	34	20	0
Clay	%	33	17	0
Liquid limit, w_L	%	59.3	53.2	-
Plastic Limit, w_P	%	31.9	35.5	-
Plasticity Index, PI		27.4	17.7	-
Moisture content, w	%	32	32	-
Specific gravity, G_s	-	2.65	2.63	2.68
Saturated Coefficient of Permeability, k_{sat}	m/s	5.00×10^{-7}	3.68×10^{-6}	3.46×10^{-2}

Basic soil hydraulic properties of the materials extracted from the SWCC are summarized in Table 2. The unsaturated coefficients of permeability of these materials were predicted from the SWCC as suggested by Leong and Rahardjo (1997) using van Genuchten, (1980) method. The hydraulic conductivity functions of these materials are presented in Figure 4.

Table 2: Hydraulic properties of the material extracted from SWCC

Description	Unit	Sandy Silt	Silty Gravel	Gravel
Saturated Volumetric water content, θ_s	m^3/m^3	0.45	0.41	0.37
Residual water content, θ_r	m^3/m^3	0.34	0.28	0.03
Residual matric suction, ψ_r	kPa	32	23	0.8
Air-entry value, A_{ev}	kPa	7	3.5	0.16

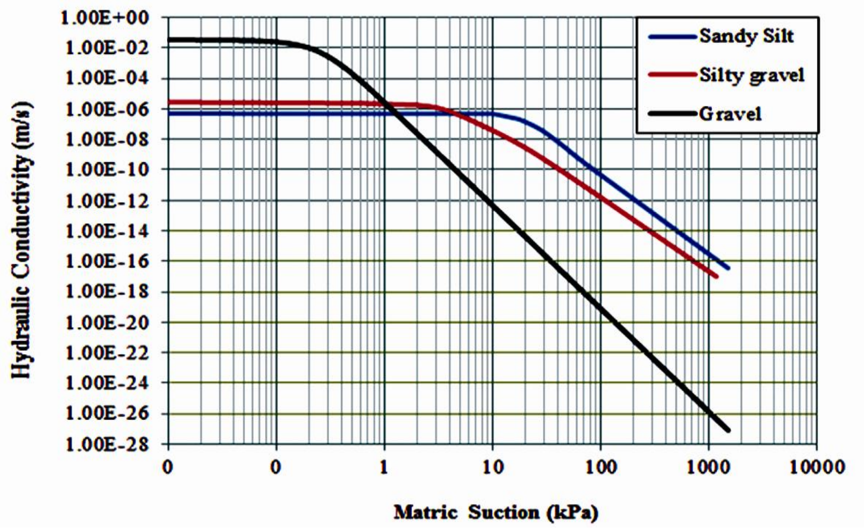

Figure 4: Hydraulic conductivity function of the materials

The rainfall intensities used in this study were determined from Intensity-Duration-Frequency (IDF) curve of Johor bahru Malaysia developed from thirty year rainfall record using equation 1 given by Department of Irrigation and Drainage (DID) and statistics of extremes given by Gumbel (1958). The IDF curve of Johor bahru Malaysia is presented in Figure 5.

$$\ln({}^{R}I_t) = a + b\ln(t) + c(\ln(t))^2 + d(\ln(t))^3 \quad (1)$$

where,
${}^{R}I_t$ = average rainfall intensity (mm/hr) for average recurrence interval (ARI) and duration t
R = Average return intervals (years)
t = Duration (minutes)
a, b, c and d are fitting constants which depends on return period and geographical location.

A 10 year return period was used in this study and the corresponding fitting constants used in equation 1 were obtained from volume 4 of MASMA (2001).

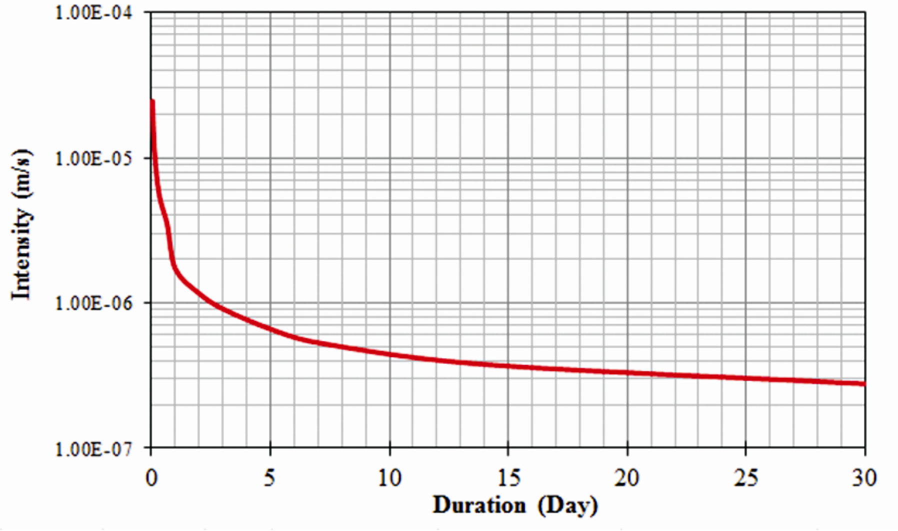

Figure 5: Intensity-Duration-Fre quency (IDF) curve of Johor bahru Malaysia

Finally the thickness of the fine-grained soil layer was varied from 0.1 m to 0.3 m at increment of 0.1 m, and also an unsaturated drainage layer of 0.1 m thickness was incorporated in the system. For each increment the variation of negative pore water pressure was determined. The schematic diagram of the modelled modified capillary barrier system is shown in Figure 6.

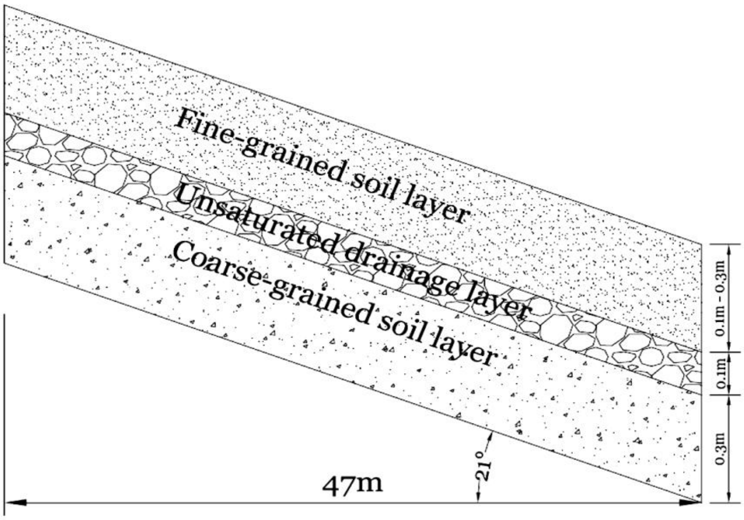

Figure 6: Capillary barrier system used in the study

3.0 Results and Discussion

The results from this study were presented and discussed inform of variation of negative pore water pressure with depth and pore water pressure with time. The depth to the interface is the critical point at which the performance of capillary barrier system can be assessed. Perhaps, once the infiltrating water penetrate the coarse-grained soil layer breakthrough have occurred which renders the system ineffective and hence more water will infiltrate into the system and results in partial and/or total elimination of the matric suction in the soil and trigger slope failure. As stated earlier, three different rainfall intensities were used in this study, therefore the presentations and discussions of the results were made sequentially from 1 hour rainfall intensity through 7 day rainfall intensity.

3.1 One Hour Rainfall Intensity

Figure 7 shows the variations of pore water pressure with depth due to 1 hour rainfall intensity for 0.3 m, 0.2 m and 0.1 m thickness of the fine-grained soil layer in a normal capillary barrier system without unsaturated drainage layer, while the same relation were shown in Figure 8 for a modified capillary barrier system with unsaturated drainage layer. In Figure 7*a*, 7*b* and 7*c* (without unsaturated drainage layer) the depth to the interface are 0.3 m, 0.2 m and 0.1 m respectively while in Figure 8*a*, 8*b* and 8*c* (modified capillary barrier with unsaturated drainage layer) the depth to the interface are 0.4 m, 0. 3 m and 0.2 m, respectively. In both Figures the negative pore water pressures were maintained throughout the rainfall duration. The negative pore water pressure after one hour rainfall was 10.2 kPa for 0.3 m and 0.2 m thickness of the fine-grained soil layer in both Figures 7 and 8 and it was 11.5 kPa and 4 kPa for 0.1 m thickness of the fine-grained soil layer in Figures 7 and 8 respectively. In the case of 0.3 m and 0.2 m thickness of the fine-grained soil layer due to one hour rainfall intensity; these thicknesses were sufficient enough to hold the infiltrating water and this is why the matric suction was low compared to 0.1 m in which the infiltrating water easily flow along the interface and into the coarse-grained soil layer (i.e. breakthrough occurrence) in Fig. 7. In Figure 8 the grain sizes of gravel created enough capillary break that causes the infiltrating water to be retained in the fine-grained soil layer and leads to low matric suction.

From Figure 7*a* the infiltrating water was retained in the fine-grained soil layer and does not reached the interface (i.e. 0.3 m) of the two soil layers. However, when the thickness of the fine-grained soil layer was reduced to 0.2 m, the infiltrating water reaches the interface (i.e. 0.2 m) before 50 minute of the rainfall duration (Fig. 7*b*), which implies that breakthrough have occurred. Similarly when the thickness of the fine-grained layer was changed to 0.1 m; the infiltrating water reaches the interface after 10 minutes and breakthrough have occurred.

In Figure 8 (for modified capillary barrier) when gravel was used as unsaturated drainage layer the infiltrating water that reaches the interface at 50 minute and 10 minutes in 7*b* and 7*c* respectively flow through the additional layer due to high particle size contrast between the upper fine-grained soil layer and the unsaturated drainage layer and the higher coefficient of permeability value of the gravel material.

Figure 9*a* and *b* were used to determine the breakthrough time for the 1 hour rainfall intensity for the two cases explained above. From Figure 9*a* there is no breakthrough when the thickness of fine-grained soil layer was 0.3 m, but breakthrough occurs at 40 and 20 minutes when the thicknesses of fine-grained soil layer are 0.2 m and 0.1 m respectively. When gravel was used as unsaturated drainage layer in the modified capillary barrier, there is no breakthrough as shown in Figure 9*b*. In fact apart from maintaining the negative pore water pressure; unsaturated drainage layer lead to small increment in matric suction with time for short duration rainfall, this is because high capillary break delayed the infiltrating water above the interface for quite some times and the pore water pressure at the interface of the unsaturated drainage layer and coarse-grained soil layer was maintained.

Therefore for one hour rainfall the thickness of fine-grained soil layer can be reduced to a minimum value and unsaturated drainage layer can be considered which can allow the infiltrated water to flow through unsaturated drainage layer due to high coefficient of permeability of the unsaturated drainage layer material.

3.2 Twenty Four Hour Rainfall Intensity

The suction distributions due to 24 hour rainfall intensity in a capillary barrier without considering the effect of unsaturated drainage layer and in a modified capillary barrier with unsaturated drainage layer are presented in Figures 10 and 11 respectively. In Figure 10*a* where the thickness of the fine-grained soil layer is 0.3 m, the infiltrating water due to the 24 hour rainfall intensity reaches the interface after 6 hours and it reaches the complete depth of 0.6 m after 16 hour of the rainfall infiltration. When the thickness of the fine-grained soil layer was changed to 0.2 m, the infiltrating water reaches the interface after 3 hour and complete depth of 0.5 m after 12 hour (Figure 10*b*). From Figure 10*c* when the thickness of the fine-grained soil layer was changed to 0.1 m, the infiltrating water reaches the interface of the two soil layers in the first one hour of rainfall infiltration and it reaches the complete depth of 0.4 m after 6 hour of rainfall infiltration. The matric suction follows the pattern of the initial condition for 0.3 m and 0.2 m thickness of the fine-grained soil layer throughout the rainfall duration. However, for 0.1 m thickness of the fine-grained soil layer the matric suction became constant before the 24 hour which indicates easy water penetration in the case of 0.1 m thick fine-grained soil layer.

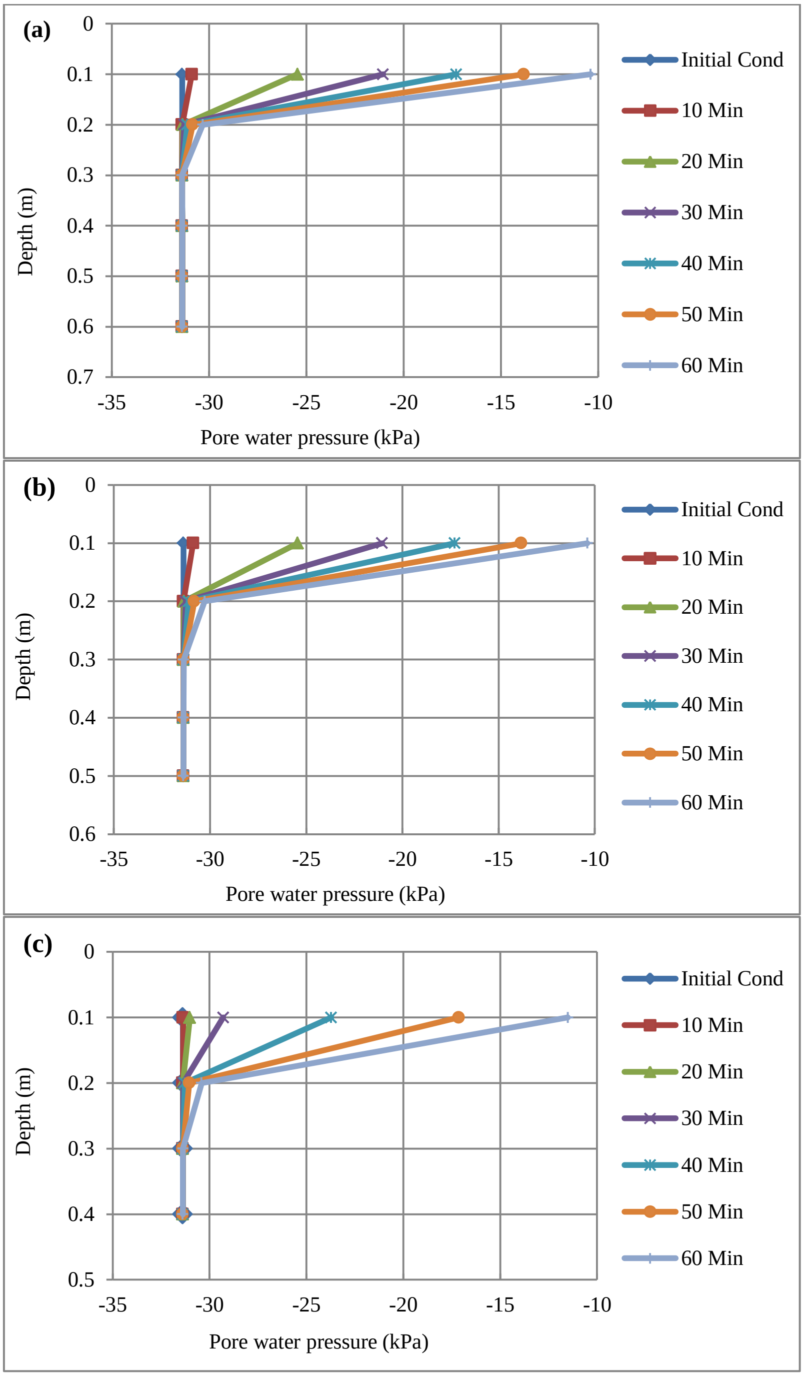

Figure 7: Variation of pore water pressure with depth due to 1 hour rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained layer, without unsaturated drainage layer

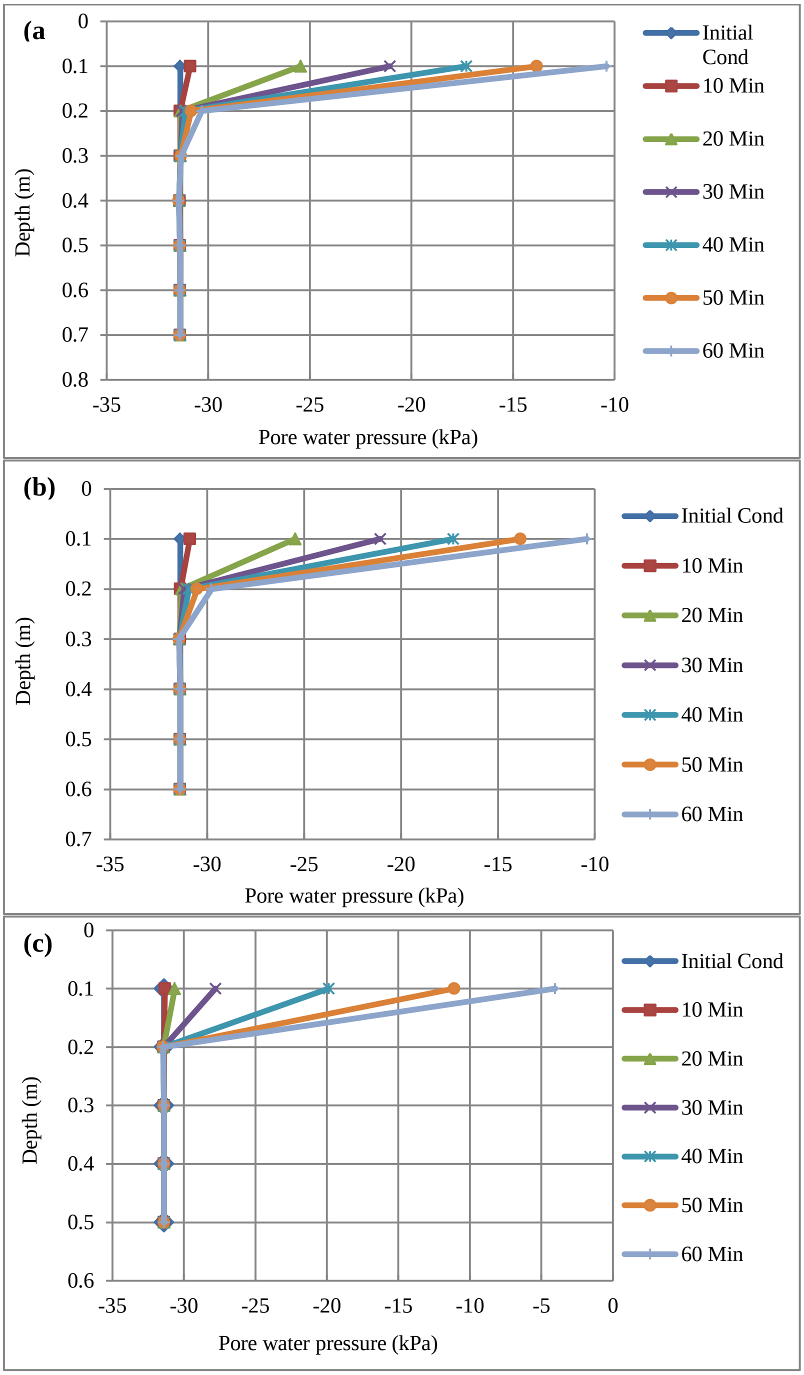

Figure 8: Variation of pore water pressure with depth due to 1 hour rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained layer, with unsaturated drainage layer

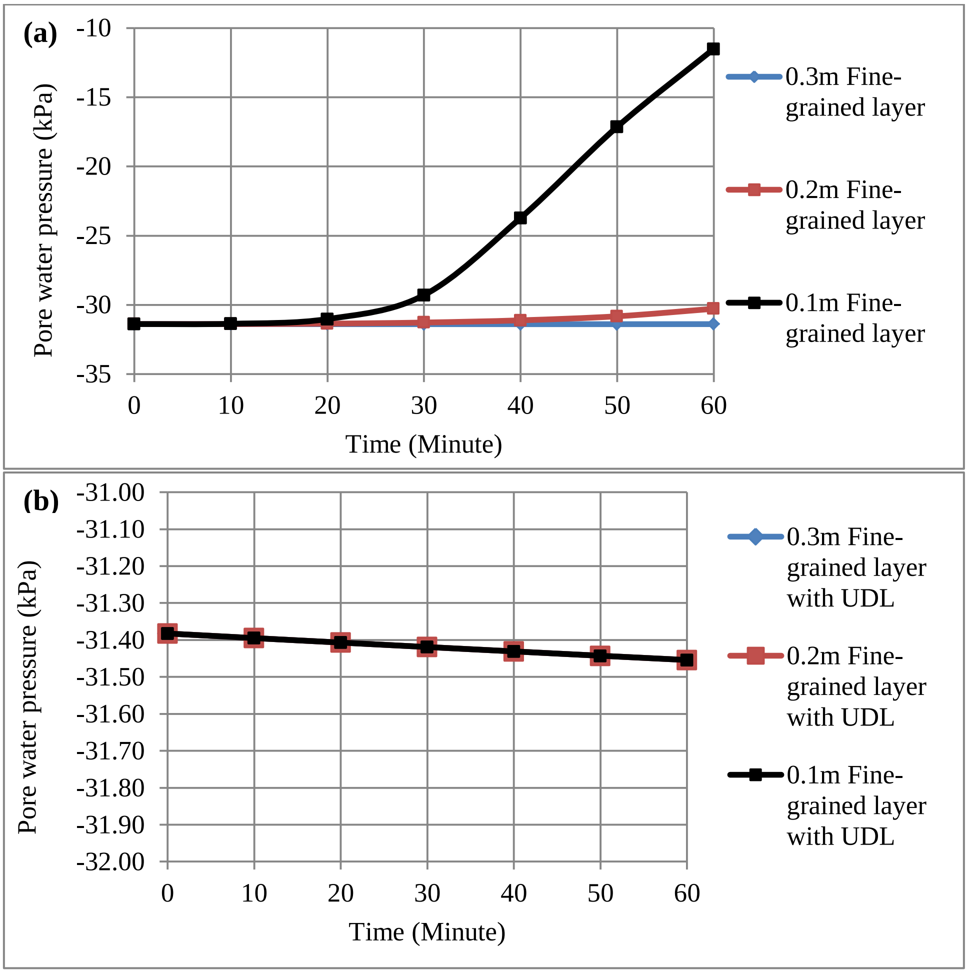

Figure 9: Variation of pore water pressure with time due to 1 hour rainfall intensity (a) without unsaturated drainage layer (b) with unsaturated drainage layer

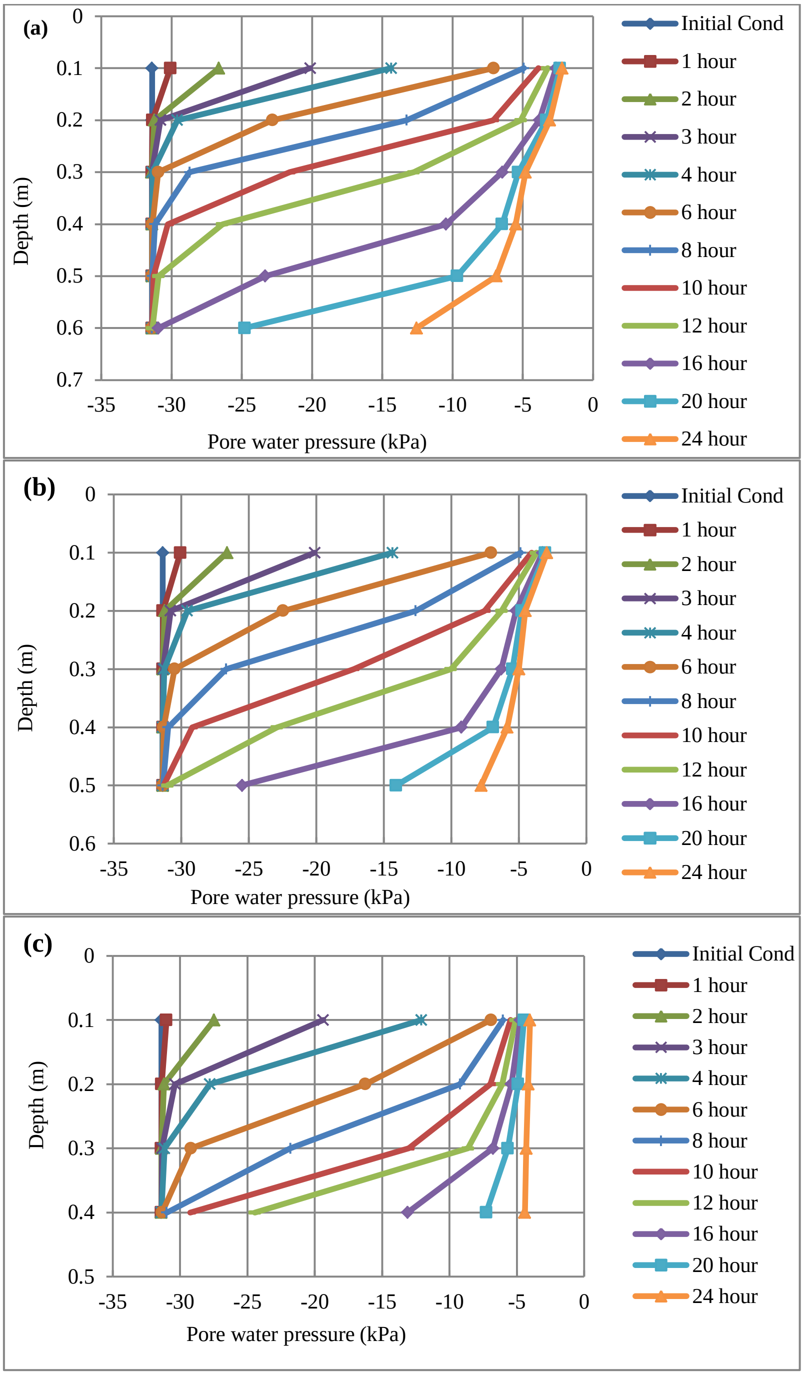

Figure 10: Variation of pore water pressure with depth due to 24 hour rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained soil layer, without unsaturated drainage layer

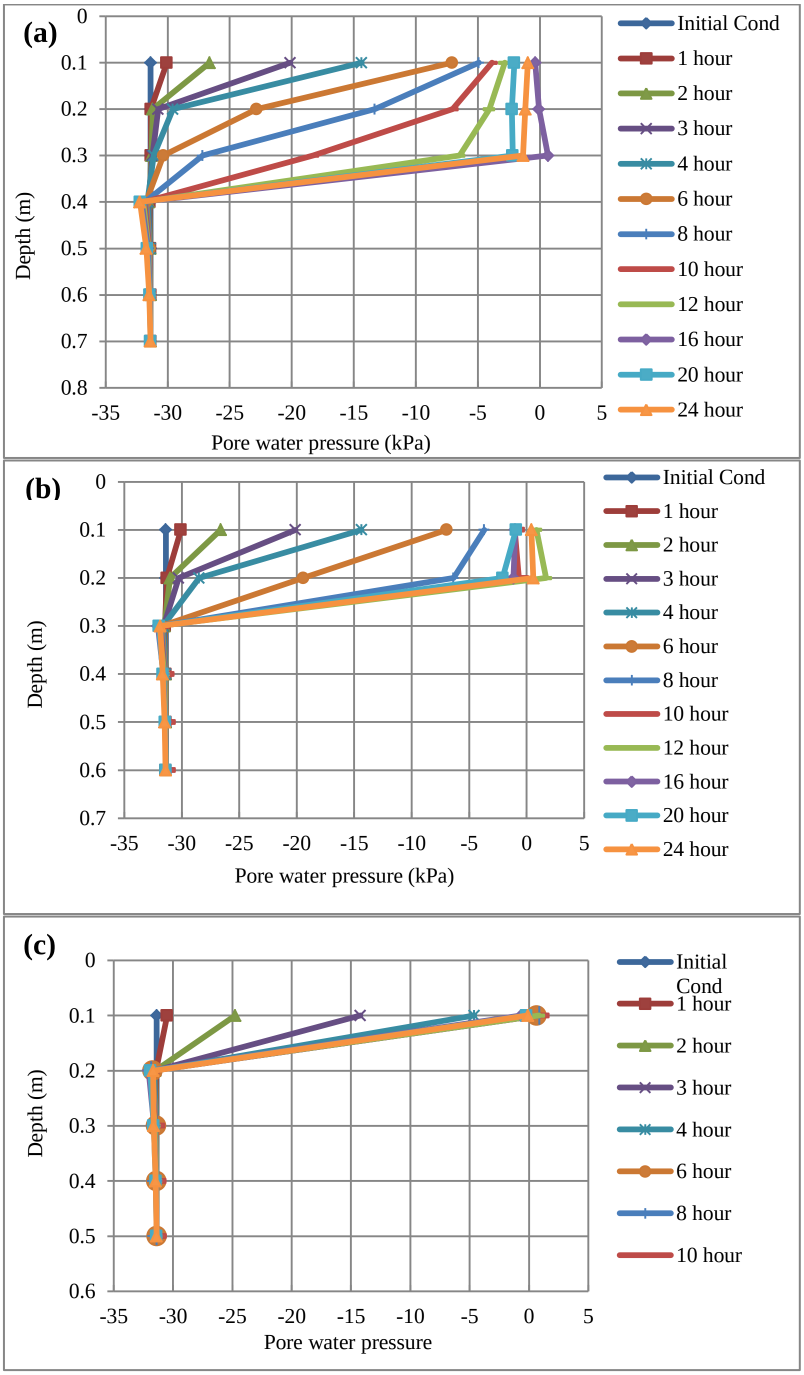

Figure 11: Variation of pore water pressure with depth due to 24 hour rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained soil layer, with unsaturated drainage layer

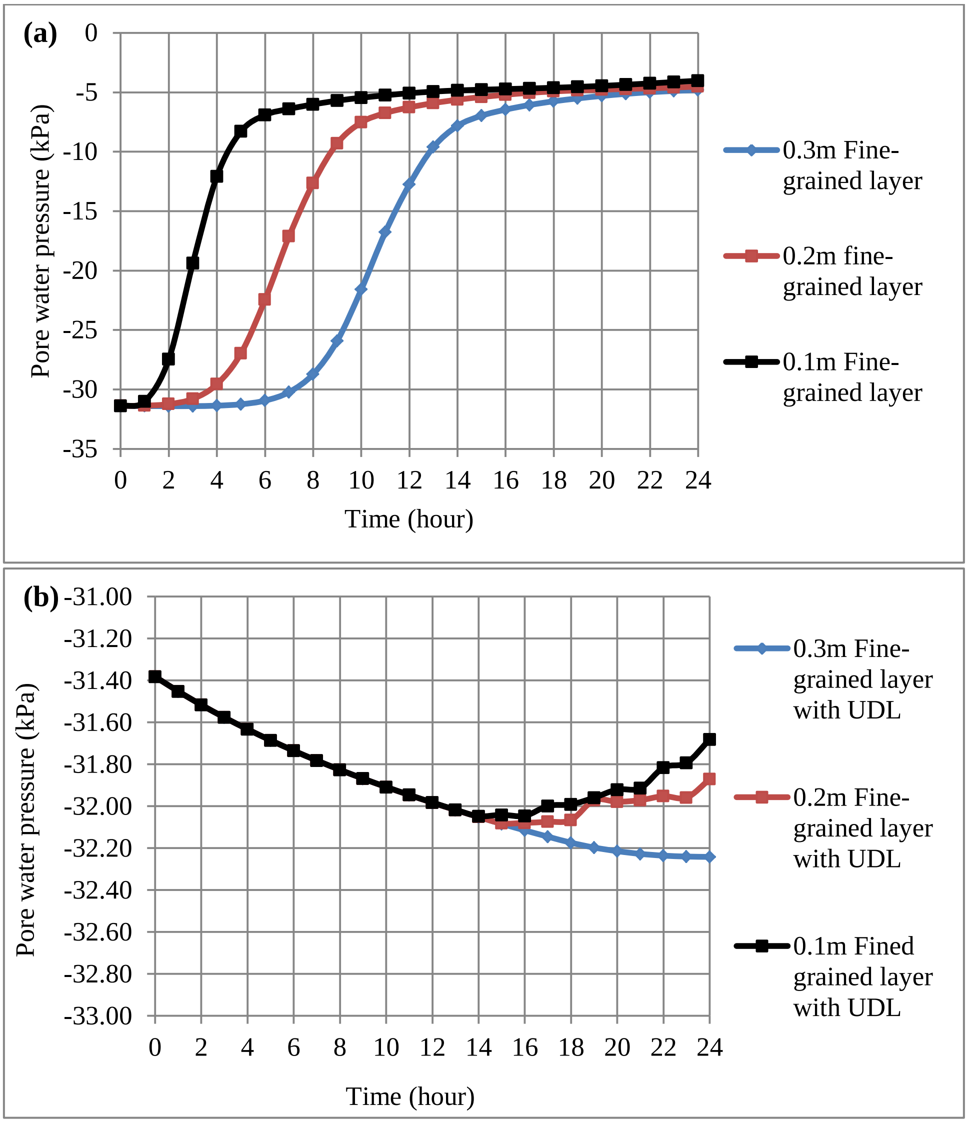

Figure 12: Variation of pore water pressure with time due to 1 hour rainfall intensity (a) without unsaturated drainage layer (b) with unsaturated drainage layer

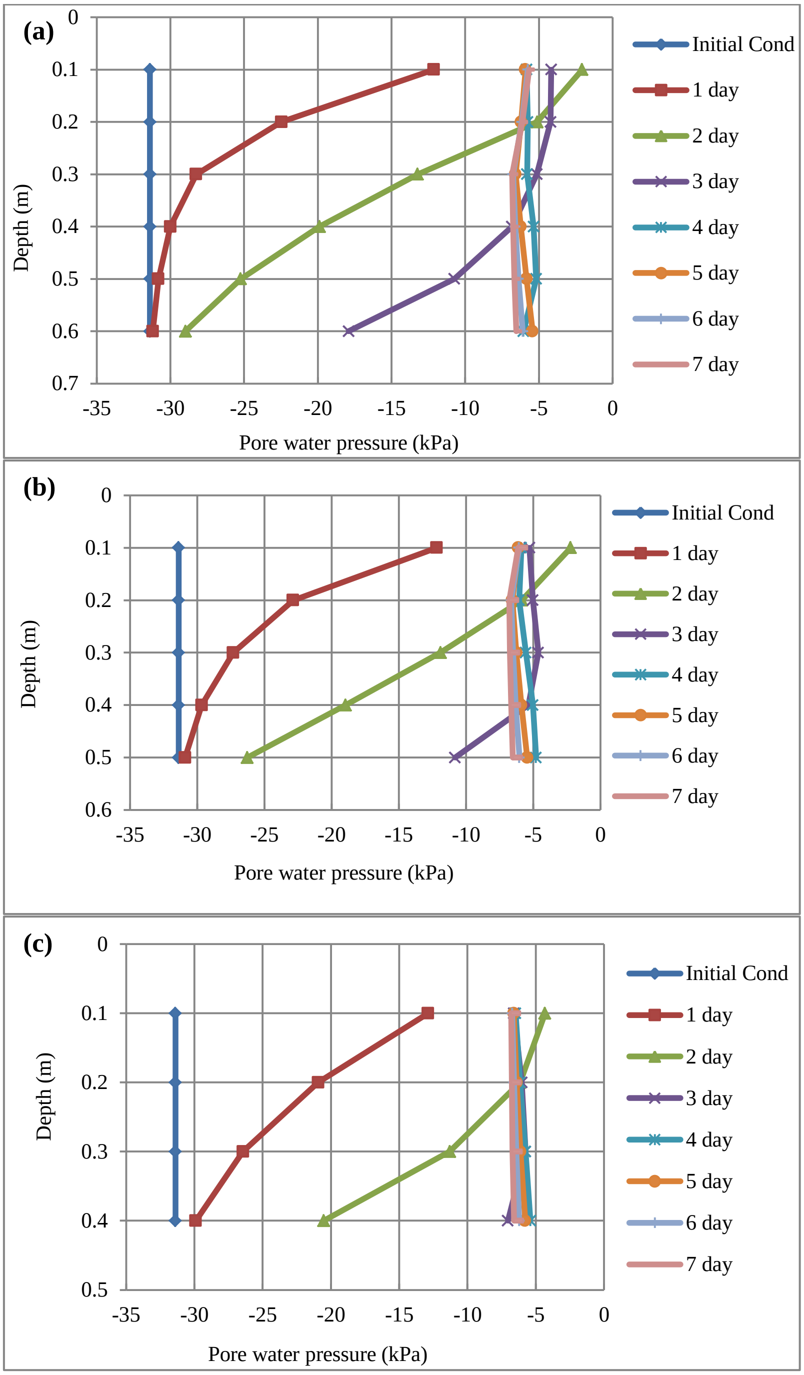

Figure 13: Variation of pore water pressure with depth due to 7 day rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained soil layer, without unsaturated drainage layer

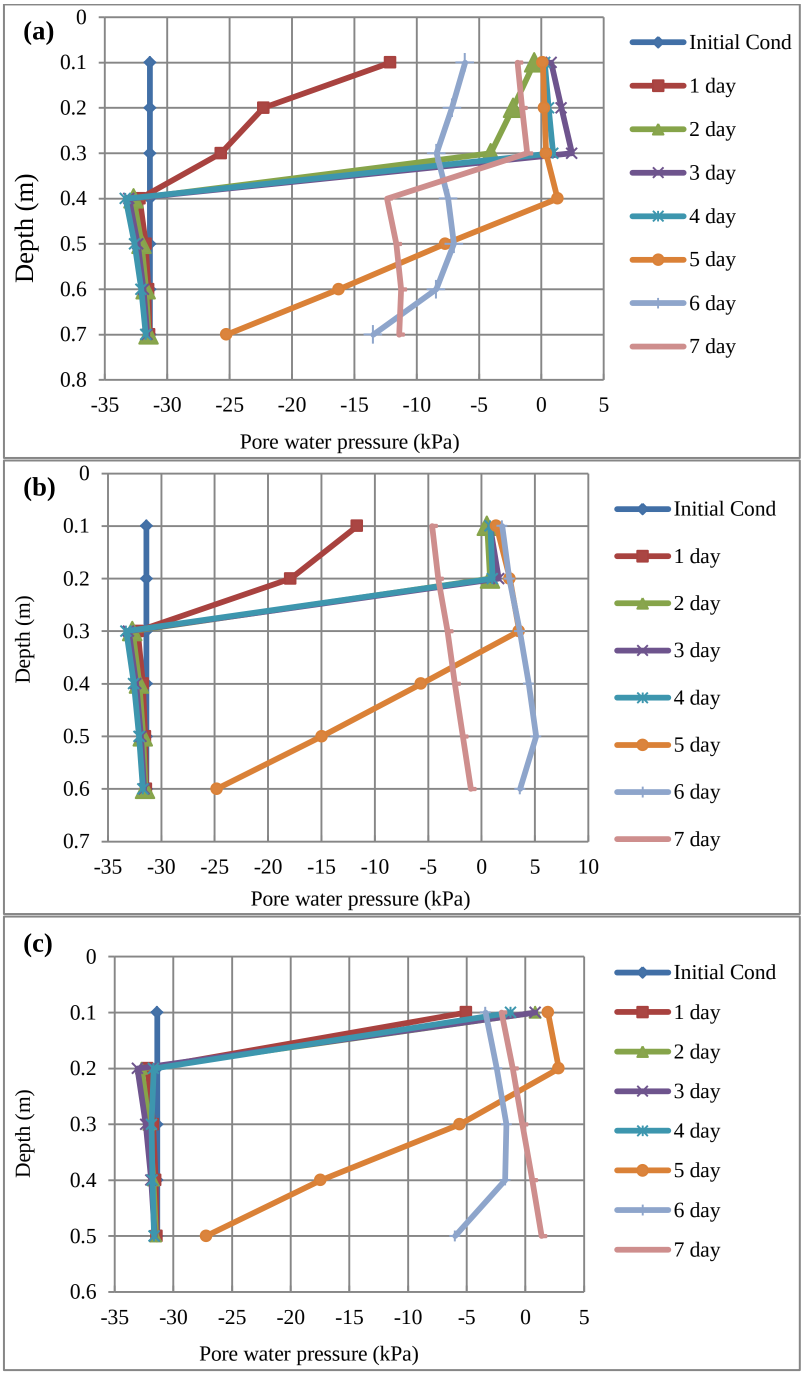

Figure 14: Variation of pore water pressure with depth due to 7 day rainfall intensity (a) 0.3 m (b) 0.2 m (c) 0.1 m fine-grained soil layer, with unsaturated drainage layer

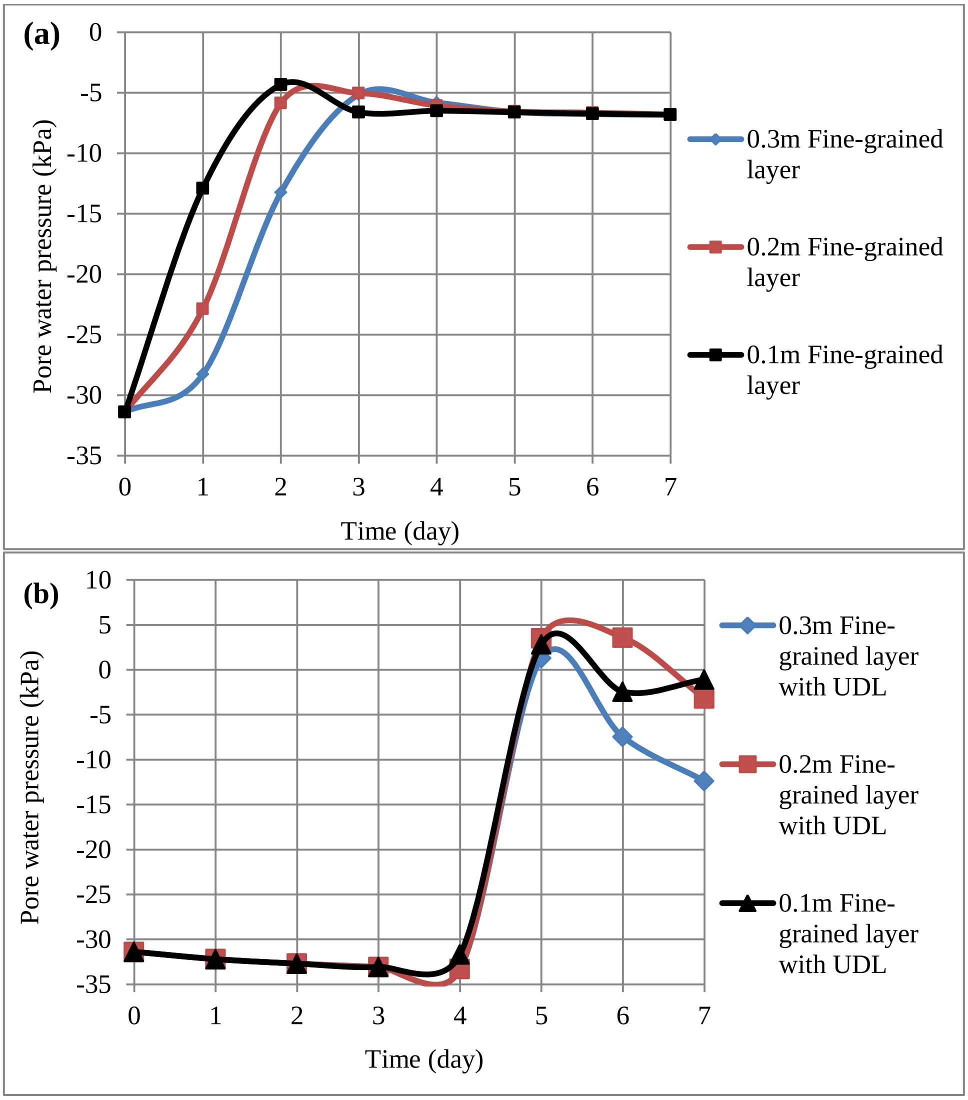

Figure 15: Variation of pore water pressure with time due to 7 day rainfall (a) without unsaturated drainage layer (b) with unsaturated drainage layer

For the modified capillary barrier with the effect of unsaturated drainage layer been considered as shown in Figure 11*a*, *b* and *c* the variation of suction only occurs within the depth of the fine-grained soil layer and it takes some time at the interface due to the effect of capillary break developed by unsaturated drainage layer materials before it flows above the gravel layer due to high coefficient of permeability of the material.

The variation of matric suction with time due to 24 hour rainfall intensity is presented in Figure 12*a*, *b* and *c*. In Figure 12*a* when the effect of unsaturated drainage layer was not considered in the capillary barrier, breakthrough occurs after 4 hour, 2 hour and 1 hour for 0.3 m, 0.2 m and 0.1 m thickness of the fine-grained soil layer respectively. The values of these suction become constant towards the end of the rainfall duration after 20 hours, this point indicates that the soil has already reaches its infiltration capacity and the quantity of rainfall that infiltrates the soil reduces and more runoff will be generated after this time. In Figure 12*b* when the effect of unsaturated drainage layer was considered (i.e. in a modified capillary barrier) there is no breakthrough occurrence and because of the capillary break developed by the unsaturated drainage layer materials it delays the water at the interface, in fact this delay causes the suction at the interface of the coarse-grained soil layer and the unsaturated drainage layer to increase but in a slow pace. The effect of the capillary break depends on the thickness of fine-grained soil layer that is why after 14 hour of rainfall infiltration, the capillary break begins to ceases due to accumulation of the infiltrating water and hence the suction due to 0.2 m and 0.1 m thickness of fine-grained soil layer starts to return to the initial suction value.

3.3 Seven Day Rainfall Intensity

The variation of suction with depth for the 7 day extreme rainfall intensity in a capillary barrier without considering the effect of the unsaturated drainage layer and when the effect of unsaturated drainage layer was considered (i.e. in a modified capillary barrier) are presented in Figures 13 and 14 respectively. From Figure 13*a*, *b* and *c* the variations of matric suction for 0.3 m, 0.2 m and 0.1 m thickness of the fine-grained soil layer follows similar pattern; the suction reaches the whole depth before 24 hour and the soil reaches its infiltration capacity after 3 days, hence, the matric suction became uniform after the 3rd day of the rainfall infiltration and the phenomena of suction redistribution occurred. In Figure 14*a*, *b* and *c* when the unsaturated drainage layer was considered (i.e. modified capillary barrier), the infiltrating water was retained in the fine-grained soil layer due to the capillary break and it reaches the interface after 4 day. There was complete elimination of the soil matric suction due to 7 day rainfall infiltration. However, this depends on the thickness of the fine-grained soil layer. In Figure 14*a* where the fine-grained soil layer is 0.3 m thick; only the suction within the fine-grained soil layer was eliminated but in Figure 14*b* where the thickness of fine-grained soil layer was 0.2 m; soil suctions were eliminated throughout the depth in 6 day but later redistribute in the7th day. In Figure 14*c* where the thickness of the fine-grained soil layer was 0.1 m, soil suctions were eliminated after 5 day and suction redistribution occurred at 6th day and later at 7th day the matric suctions at greater depth were eliminated.

The variations of the matric suction with time in a capillary barrier without unsaturated drainage layer and with unsaturated drainage layer are presented in Figure 15*a* and *b* respectively. From Figure 15*a* when there is no unsaturated drainage layer the breakthrough occurs in less than 1 day in all the three selected thickness of the fine-grained soil layer and the soil suction became uniform after fourth day because the soil have reached its infiltration capacity. In Figure 15*b* breakthrough occurs after 4th day and the soil suction start to redistribute after 5th day.

4.0 Conclusions

Numerical analyses were conducted to investigate the effect of fine-grained soil layer thickness on the performance of capillary barrier constructed from residual soil with unsaturated drainage layer at the interface. Based on the result of the analyses the following conclusions were drawn:

Inclusion of unsaturated drainage layer in a capillary barrier constructed with the residual soil results in large particle size contrast between the fine-grained soil layer and the unsaturated drainage layer which results in capillary break that impedes water infiltration into underlying soil layer.

For one hour rainfall intensity, provided the thickness of the fine-grained soil layer is greater than or equal to 0.3 m the infiltrated water can be stored in the fine-grained soil layer by capillary forces without breakthrough occurrence. However, if the thickness of the fine-grained soil layer is below 0.3 m there is need for inclusion of unsaturated drainage layer so as to prevent breakthrough occurrence.

For a 24 hour rainfall intensity, breakthrough occurs even when the thickness of the fine-grained soil layer is considered as 0.3 m, this show that provided the rainfall intensity to be considered is up to 24 hour it is necessary to include unsaturated drainage layer which helps in reducing the thickness of the fine-grained soil layer to even 0.1 m without breakthrough occurrence.

For 7 day rainfall intensity, inclusion of unsaturated drainage layer causes the delay in the breakthrough occurrence from less than a day to 4 day irrespective of the thickness of the fine-grained soil layer.

Apart from maintaining soil suction; the inclusion of unsaturated drainage layer also leads to an increase in the soil suction in slow pace until when the capillary break ceases and water start to flow above the unsaturated drainage layer, then the increase in the soil suction depends on the thickness of the fine-grained soil layer as well as duration of the rainfall intensity.

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