EFFECTIVENESS OF UNSATURATED DRAINAGE LAYER IN WATER DIVERSION UNDER DIFFERENT RAINFALL CONDITIONS

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Abstract: The concept of capillary barrier principle is widely applied as lasting solution to rainfall infiltration in unsaturated soil slope. However, the performance of a capillary barrier system normally reduced as rainfall duration gets longer, due excessive rainfall infiltration. Therefore this paper uses numerical modeling approach to highlights the effectiveness of a capillary barrier system with unsaturated drainage layer at interface to improve its performance under three different rainfall conditions. The capillary barrier system was constructed using residual soil obtained within the compound of Universiti Teknologi Malaysia, Johor Bahru campus; with sand and gravel employed as unsaturated drainage layer. The system was subjected to rainfall intensities of 1 hour, 1 day and 7 days obtained from Intensity-Duration-Frequency (IDF) curve of Johor Bahru, Malaysia. The results show that high intensity short duration rainfall has less effect on eliminating soil matric suction completely, however the near surface matric suction was eliminated due to prolonged rainfall infiltration and a capillary barrier system constructed with gravel as unsaturated drainage layer is more effective in diverting the infiltrated water before breakthrough occurs under all the rainfall conditions.

Keywords: *Slope failure, Capillary barrier, unsaturated drainage layer, Residual soil, IDF Curve*

1.0 Introduction

Slope failures are a common geotechnical problem and often most devastating natural disaster that occur frequently in many tropical climate regions of the world, and rainfall infiltration is considered as the most significant triggering factor to these type of failures in these regions which are characterized with hot and humid climatic conditions (Brand, 1984; Chen *et al.*, 2004; Collins and Znidarcic, 2004; Lee *et al.*, 2009; Tsaparas *et al.*, 2002).

In tropical climate countries water table mostly exists at great depth and the residual soil above the water table is believed to exist in unsaturated condition with presence of negative pore water pressure which contributes additional shear strength to the unsaturated residual soil (Fredlund and Rahardjo, 1993; Fredlund *et al.*, 2012). These additional shear strength provided by the matric suction usually decreases or even disappears due to rainfall infiltration which make the unsaturated slope to be more susceptible to failure (Rahardjo *et al.*, 2005; Rahardjo, 1995).

Different alternative solutions such as the use of 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 in unsaturated soil slope. Among these preventive measures capillary barrier is considered as the most promising alternative solution against rainfall infiltration (Li *et al.*, 2013).

A capillary barrier is an earthen cover which comprises of an unsaturated fine-grained soil layer overlying an unsaturated coarse-grained soil layer (Ross, 1990; Stormont, 1996) which works on the basis of capillary break that occur at the interface of the two soil layers. The contrast in particle sizes of the two soils in a capillary barrier results in different unsaturated hydraulic properties in the system (Fredlund and Rahardjo, 1993).

Water that infiltrates in to the capillary barrier system is normally stored in the fine-grained soil layer before later been removed by evaporation or evapotranspiration processes, and according to Li*, et al.*, (2013); when the cover soils is initially wet the effectiveness of cover with capillary barrier effect cannot be guaranteed and additional measure should be taken. One of the additional measures is the used of unsaturated drainage layers.

An unsaturated drainage layer is an additional layer of different soil material of high permeability constructed above the interface of fine-grained and coarse-grained soil layers so that infiltrated water can flow through this layer due to the sloping surface (Stormont and Morris, 1997)**.**

Therefore this paper compares the performance of two types of materials (fine sand and gravel) as unsaturated drainage layer in a capillary barrier system constructed with residual soil in diverting the infiltrated water before breakthrough occurs.

2.0 Material and Methods

Four types of soils were used in this study and they include the Sandy Silt, Silty Gravel, Fine Sand and Gravel. The Sandy Silt and Silty Gravel are the original soil from Balai Cerapan site, located within Universiti Teknologi Malaysia, Johor Bahru campus while the fine sand and the gravel were commercially obtained and the gravel is from crushed granite. The arrangement of the soil at the site is in such a way that sandy silt overlaid the silty gravel which typically formed a natural capillary barrier system due to particle size contrast of the two soil layers downward. This typical arrangement of the soil layers at the site is shown in Figure 1. Soil classification test, permeability test and pressure plate test were conducted based on the standard procedure outlined in the British standard (BSI) and American Society for Testing and Materials (ASTM). The soil classification test was conducted using procedure outlined in BS 1337 Part 2: 1990 (BSI, 1990). The saturated permeability functions (k_{sat}) of the materials were obtained from falling head and constant head permeability tests as described in BS 1377: Part 5:1990, while the soil water characteristic curve (SWCC) test was conducted using a pressure plate apparatus based on recommended procedure outlined in ASTM D6836-02 (ASTM, 2008). The unsaturated hydraulic conductivity function of the soil was predicted from the SWCC using van Genuchten

(1980) method as suggested by Leong and Rahardjo (1997). The Summary of the soil properties used in this study is presented in Table 1 while the particle size distribution, soil water characteristics and the unsaturated coefficient of permeability curves are presented in Figure 2, 3 and 4 respectively.

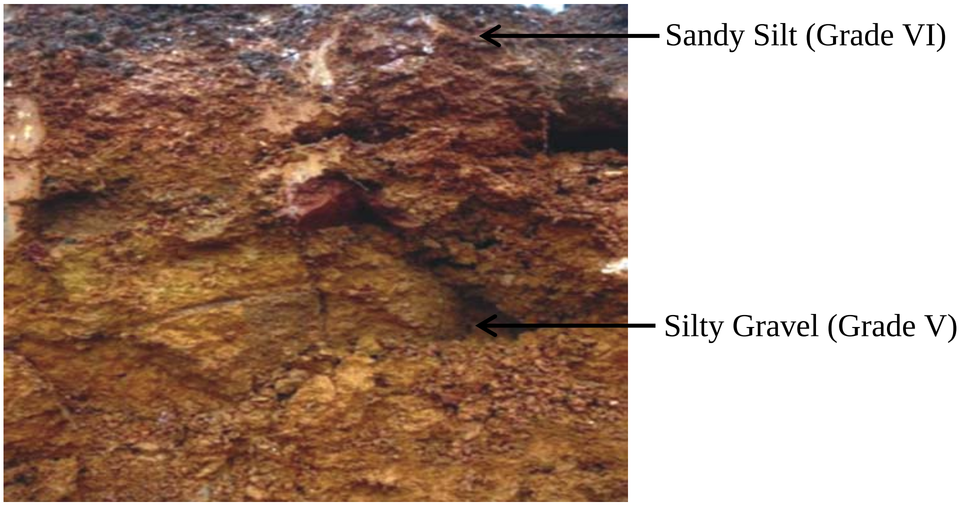

Figure 1 Typical soil layers arrangement in the site

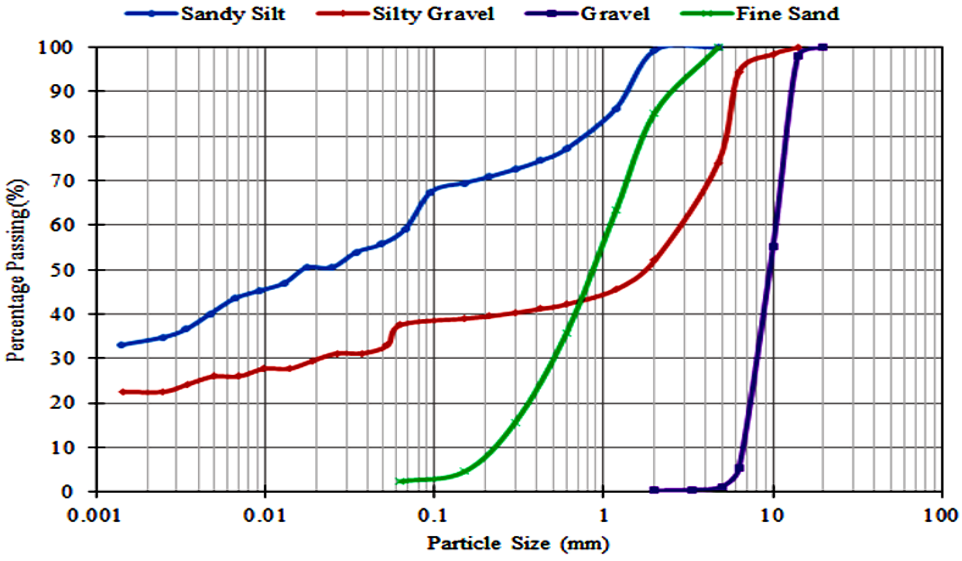

Figure 2 Particle Size Distribution Curve of the materials

Table 1 Basic and hydraulic properties of the materials

Description	Unit	Sandy Silt	Silty Gravel	Sand	Gravel
1. Basic Soil Properties					
British Soil Classification system	-	MHS	GMH	SP	SP
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	2.65	2.68
Saturated Coefficient of Permeability, k_{sat}	m/s	$5.00\text{x}10^{-7}$	$3.68\text{x}10^{-6}$	$2.88\text{x}10^{-4}$	$3.46\text{x}10^{-2}$
2. Hydraulic Properties of the soil					
Saturated Volumetric water content, θ_s	m^3/m^3	0.45	0.41	0.44	0.37
Residual water content, θ_r	m^3/m^3	0.34	0.28	0.04	0.03
Residual matric suction, ψ_r	kPa	32	23	4	0.8
Air-entry value, A_{ev}	kPa	7	3.5	0.28	0.16

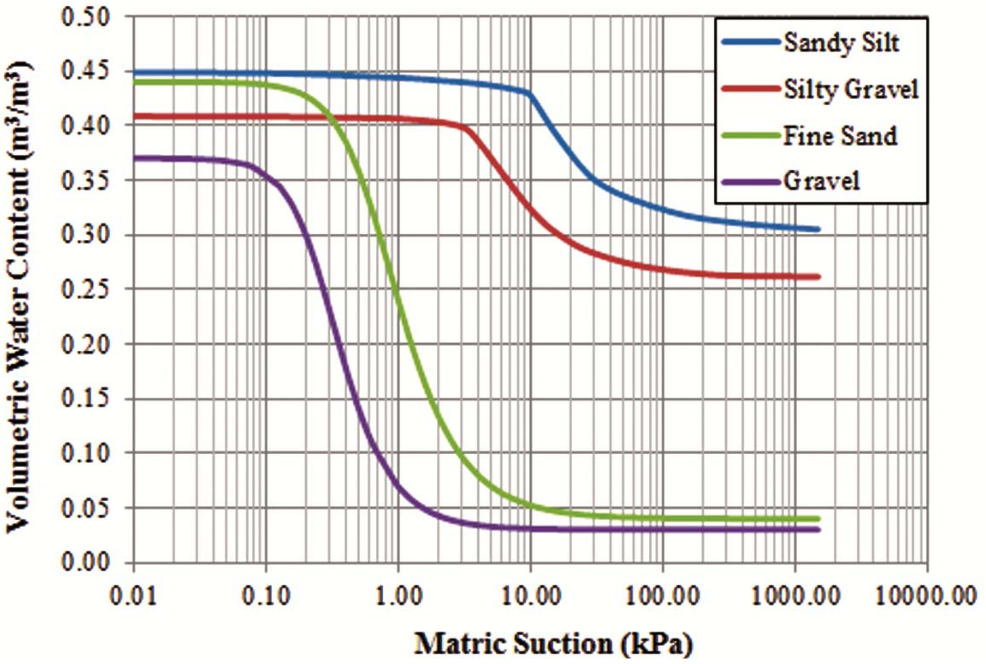

Figure 3 Soil Water Characteristics Curve of the material

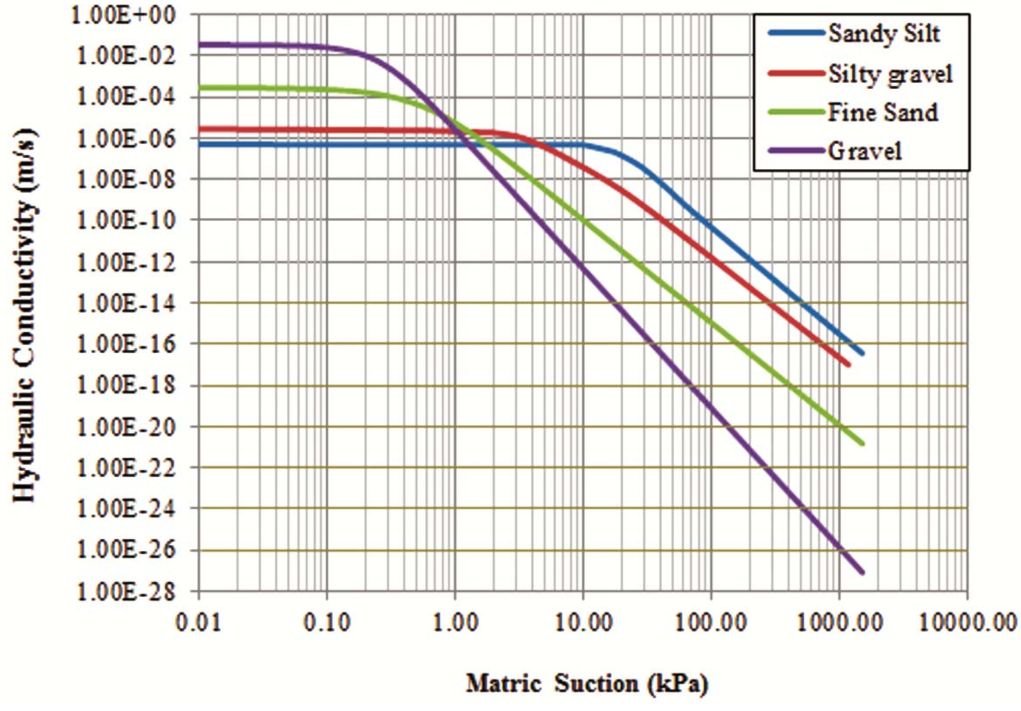

Figure 4 Unsaturated Hydraulic conductivity function of the materials

The rainfall intensity used in this study was obtained from an intensity-duration-frequency (IDF) curve of Johor Bahru Malaysia, which was developed with 30 year rainfall data of a site in Johor Bahru using established coefficient given by Department of irrigation and Drainage, Malaysia and Gumbel's distribution. The IDF curve of Johor Bahru is presented in Figure 5. From this Figure the rainfall intensity decrease with increase in duration which is typical characteristics of rainfall.

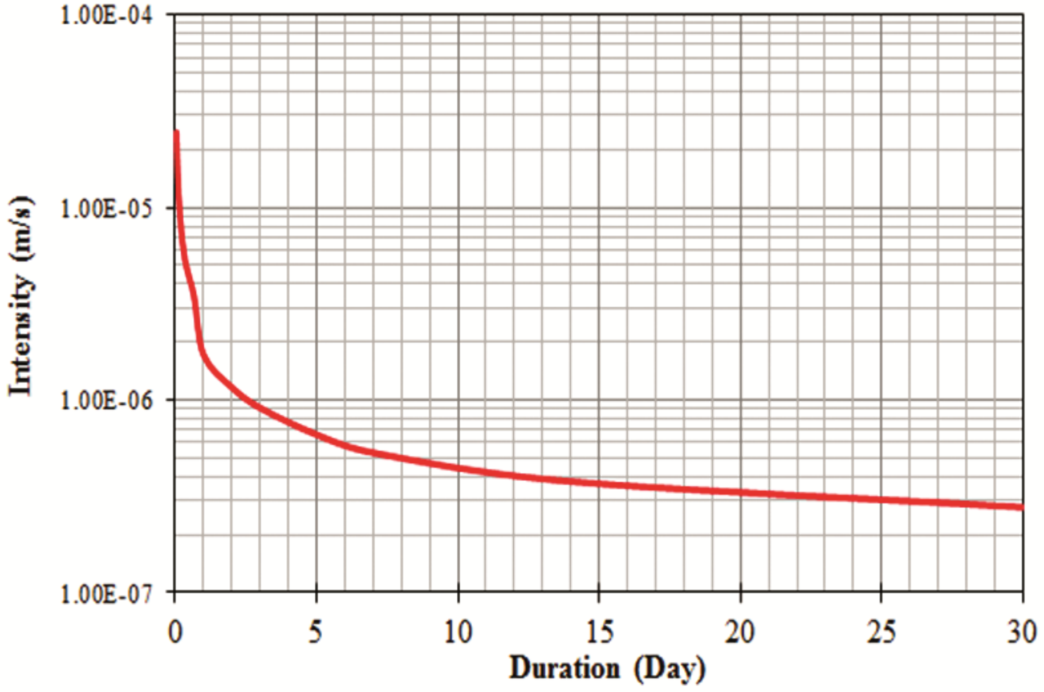

Figure 5 Intensity-Duration-Frequency (IDF) Curve of Johor Bahru

The geometry and soil properties of an infinite slope located at Balai Cerapan in UTM Johor bahru campus were used in the numerical analysis. The slope has an approximate slope angle of 21^0 and horizontal length of 47m. SEEP/W (Geo-SlopeInternational, 2007a) was used for the numerical analysis using hydraulic properties of the soil as input parameters. The geometry of the modeled slope is presented in Figure 6. The fine-grained and coarse-grained soil layers are of 0.3m depth each and 0.1m thick unsaturated drainage layer was imposed at the interface of these residual soils. Three different boundary conditions were assigned to the slope model. The left and right edges above the water table and the bottom of the modelled slope were specified as a no flow boundaries (i.e. $Q = 0$), while the edges below the water table were assigned as head boundaries with pressure head equal to the vertical distance from the datum to the water table level. These boundary conditions enhance the lateral flow to occur within the saturated zone of the modelled slope. Finally the top boundary was set as unit flux boundary (q) which is equal to the magnitude of the rainfall intensity.

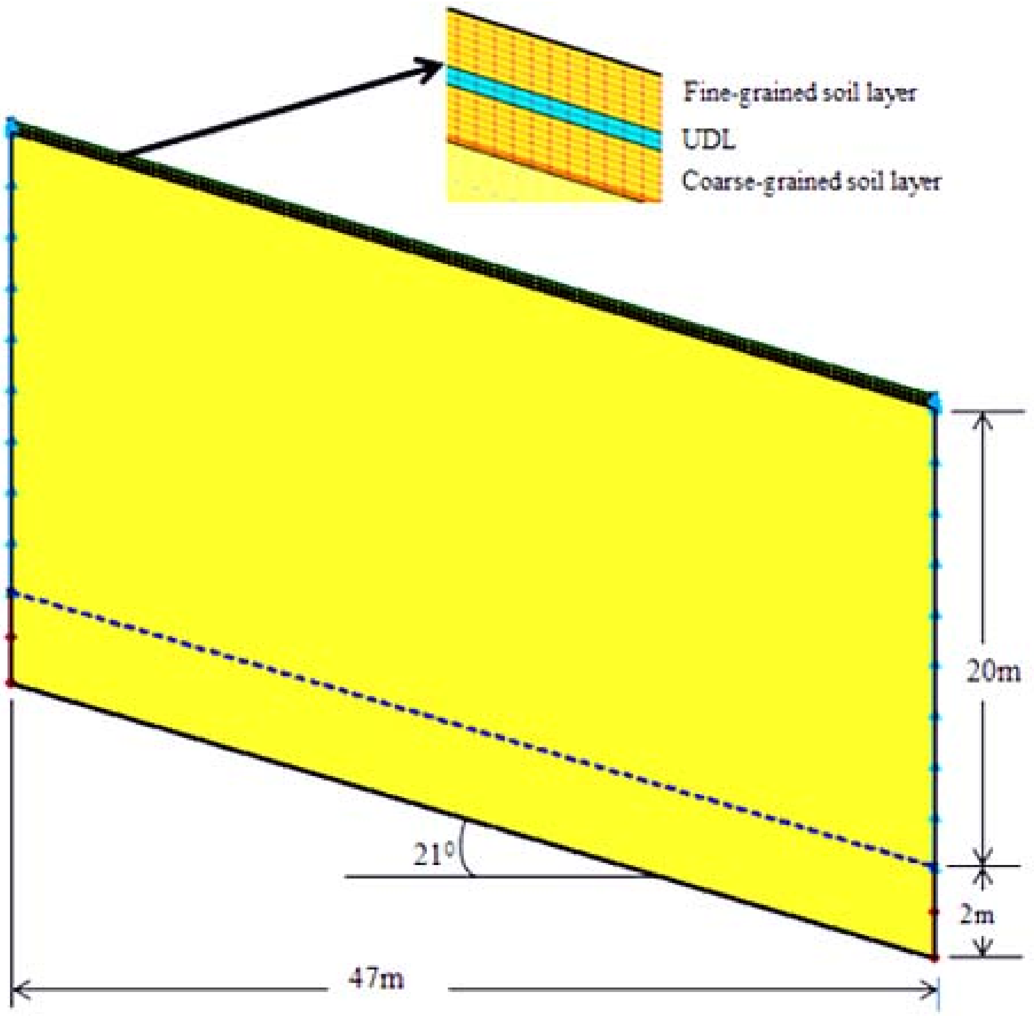

Figure 6 Simulated slope

3.0 Results and Discussions

Three types of rainfall were used in this study and they include a 1 hour rainfall which is characterized with high intensity (Figure 5) and is classified as high intensity short duration rainfall. 1 day rainfall which relatively has medium intensity compared to 1 hour rainfall and a 7 day rainfall which has low intensity and was selected to cover the short intensity long duration rainfall and antecedent rainfall condition.

Results from these analyses were presented and discussed in form of pore water pressure versus depth and pore water pressure versus time. Pore-water pressure versus depth shows the pattern of changes in pore water pressure with changes in depth and the advancement of the wetting front as rainfall continues to infiltrate in to the slope. On the other hand the results of pore water pressure versus time shows the approximate time at which breakthrough occur.

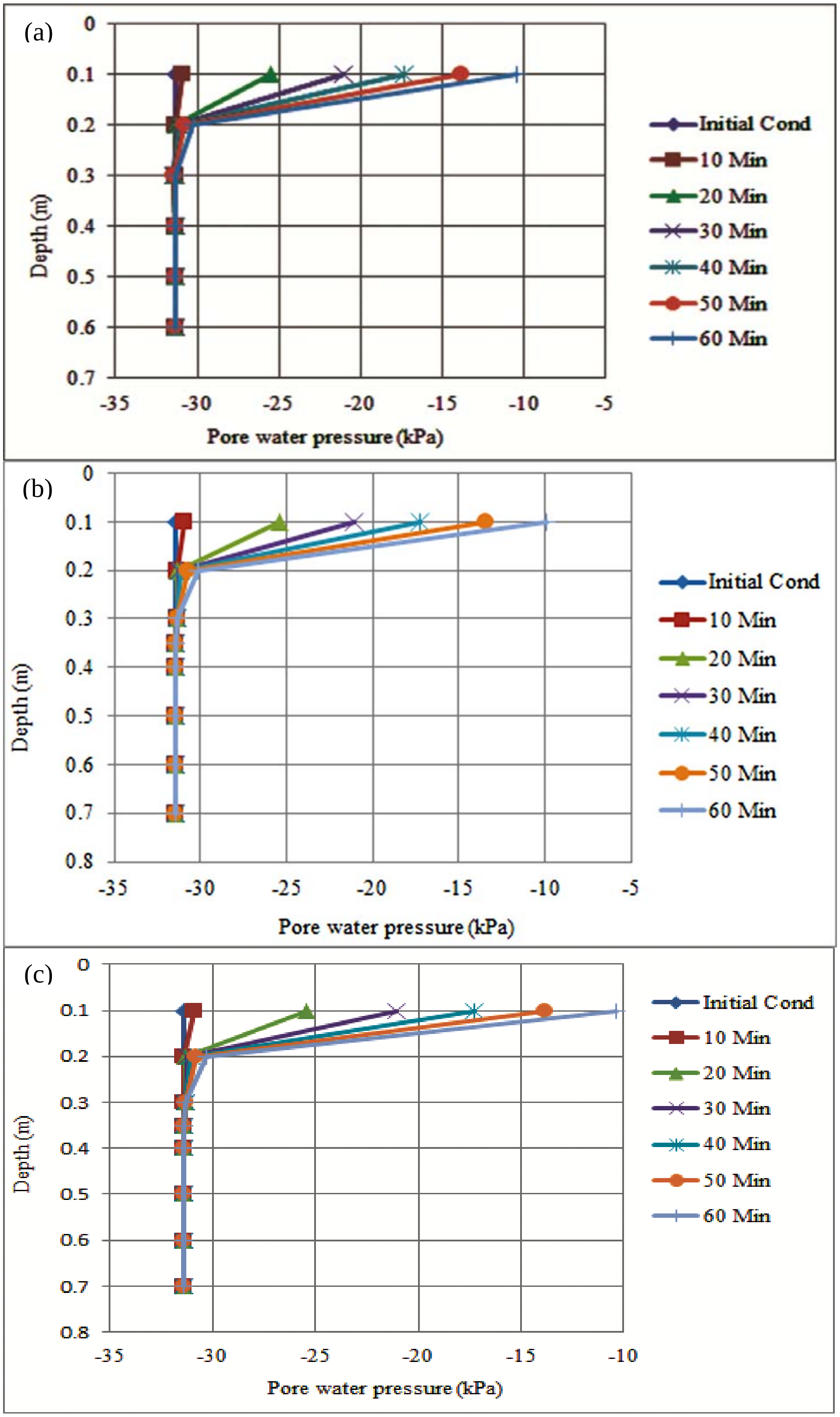

Figure 7 suction distributions with depth due to 1 hour rainfall (a) without additional layer (b) With sand layer (c) with gravel layer

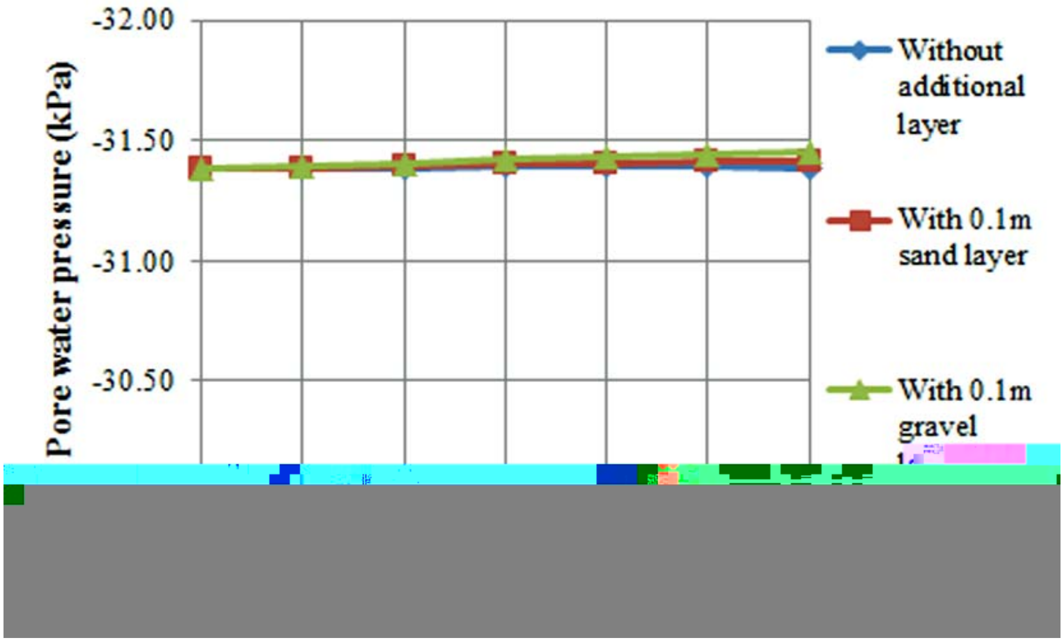

Figure 8 suction distributions with time due to 1 hour rainfall

For one hour rainfall infiltration as shown in Figure 7*a*, *b* and *c*; the rainfall infiltration significantly affects the matric suction up to 0.2m depth from the surface of the covered slope, matric suction beyond this depth are only slightly affected; this means the infiltrated water does not reach the interface of the two soil layers, and for this types of rainfall the infiltrated water is normally retained within the fine-grained soil layer which can later be removed through other processes such as evaporation and transpiration. Figure 8 depicts the variation of pore water pressure with time for this rainfall intensity and this figure clearly shows that the infiltrated water does not reached the interface (coarse-grained soil layer) throughout the duration of rainfall.

The variation of negative pore water pressure with depth for 24 hour rainfall is presented in Figure 9*a*, *b* and *c*. Breakthrough into the coarse-grained soil layer occurs in Figure 9*a* and *b* due rainfall infiltration, whereas the infiltrated water completely flow through the unsaturated drainage layer and prevent breakthrough occurrence in Figure 9*c*. From Figure 10; breakthrough occurs after 6 hour and 12 hours for the system without unsaturated drainage layer and with sand as unsaturated drainage layer respectively, but the negative pore water pressure was maintained throughout the duration of rainfall when gravel was used as unsaturated drainage layer. As it can be observed from Figure 9*c* at 16 hour of the rainfall infiltration the pore water pressure changes to positive close to 0.3m depth, this is because of the capillary break between grade VI residual soil and the gravel layer therefore the infiltrated water accumulated at the interface of these materials before it enters and flow through the drainage layer. Therefore, negative pore water pressure was maintained throughout the duration of rainfall in all the three cases.

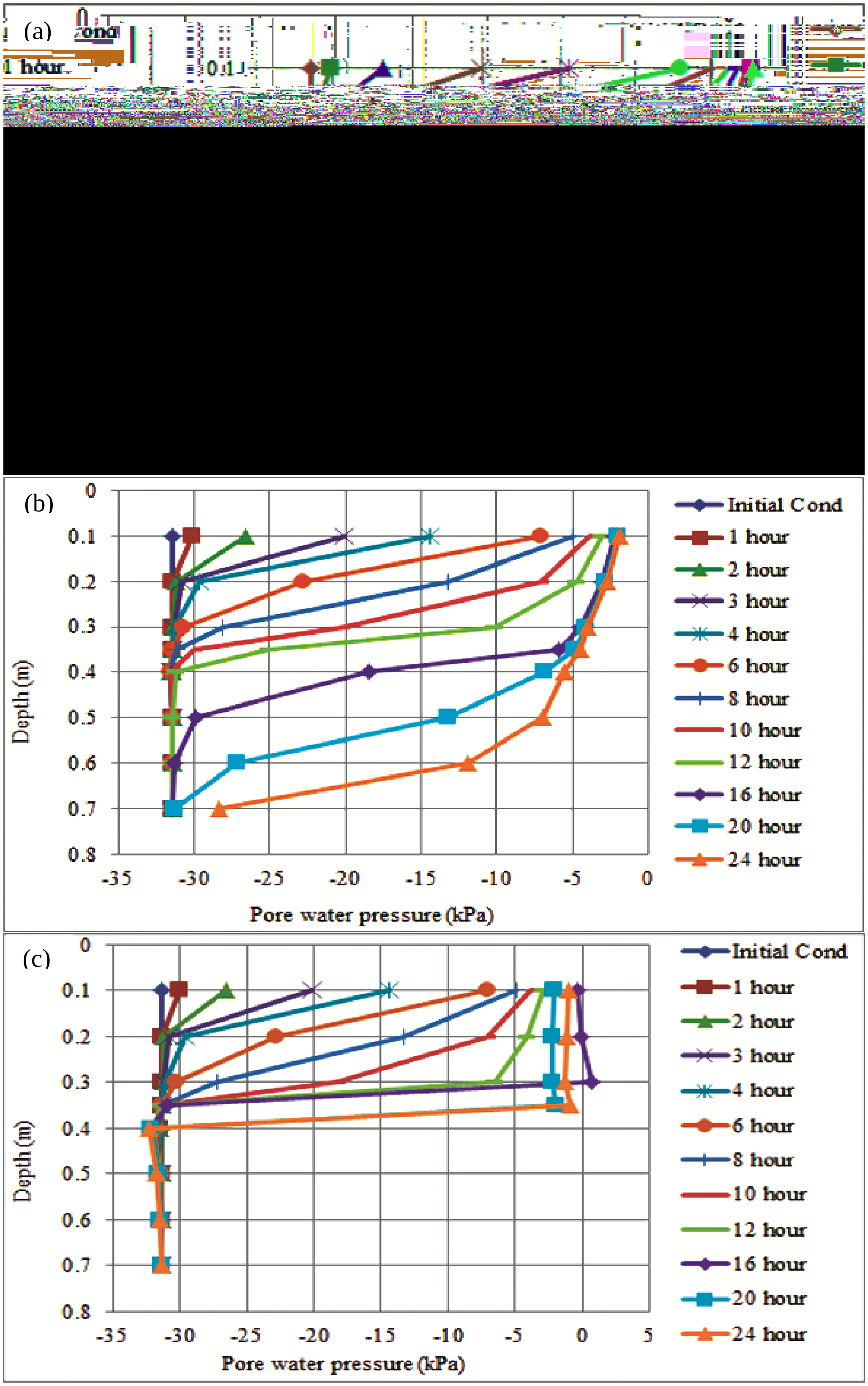

Figure 9 suction distributions with depth due to 24 hour rainfall (a) without additional layer (b) With sand (c) with gravel

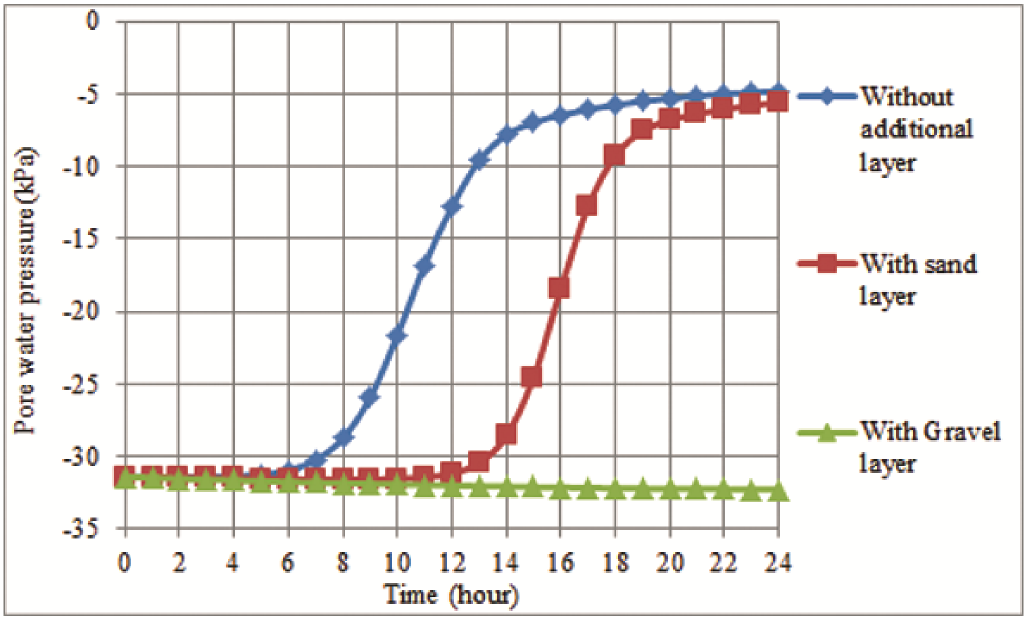

Figure 10 suction distributions with time due to 24 hour rainfall

The performance of sand as unsaturated drainage layer does not prevent breakthrough occurrence because the particle sizes of the sand and top grade VI residual soil is similar which provide less capillary break at their interface which can easily disappear due water accumulation at the interface.

The variation of negative pore water pressure with depth for seven day rainfall is presented in Figure 11*a*, *b* and *c*. In Figure 11*a* the infiltrated water reaches the interface of the two-soil layer in less than 24 hour from the beginning of the rainfall and it reaches the complete depth of 0.6m after the second day. The negative pore water pressure completely reaches equilibrium (uniform) due to continues rainfall infiltration after the 3rd day of rainfall infiltration, but when sand is employed as unsaturated drainage layer the infiltrated water reaches the interface of the coarse-grained soil layer after the second day of the rainfall infiltration and it reaches the complete depth after the third day of the rainfall event, the suction reaches equilibrium after fifth day of the infiltration. When gravel was used as unsaturated drainage layer; the infiltrated water reaches the interface after the fourth day of the rainfall event, it completely reaches the whole depth after the fifth day. After the rainfall infiltration on the fifth day, suction redistribution occurs. But in this case the pore water pressure becomes positive when gravel was employed as unsaturated drainage layer due high capillary break developed at the interface. In Figure 12 the breakthrough occurs in less than a day and after one day for the case of system without unsaturated drainage layer and the system with sand as unsaturated drainage layer respectively. And when gravel was used as unsaturated drainage layer the breakthrough occur after the fourth day of the rainfall infiltration process.

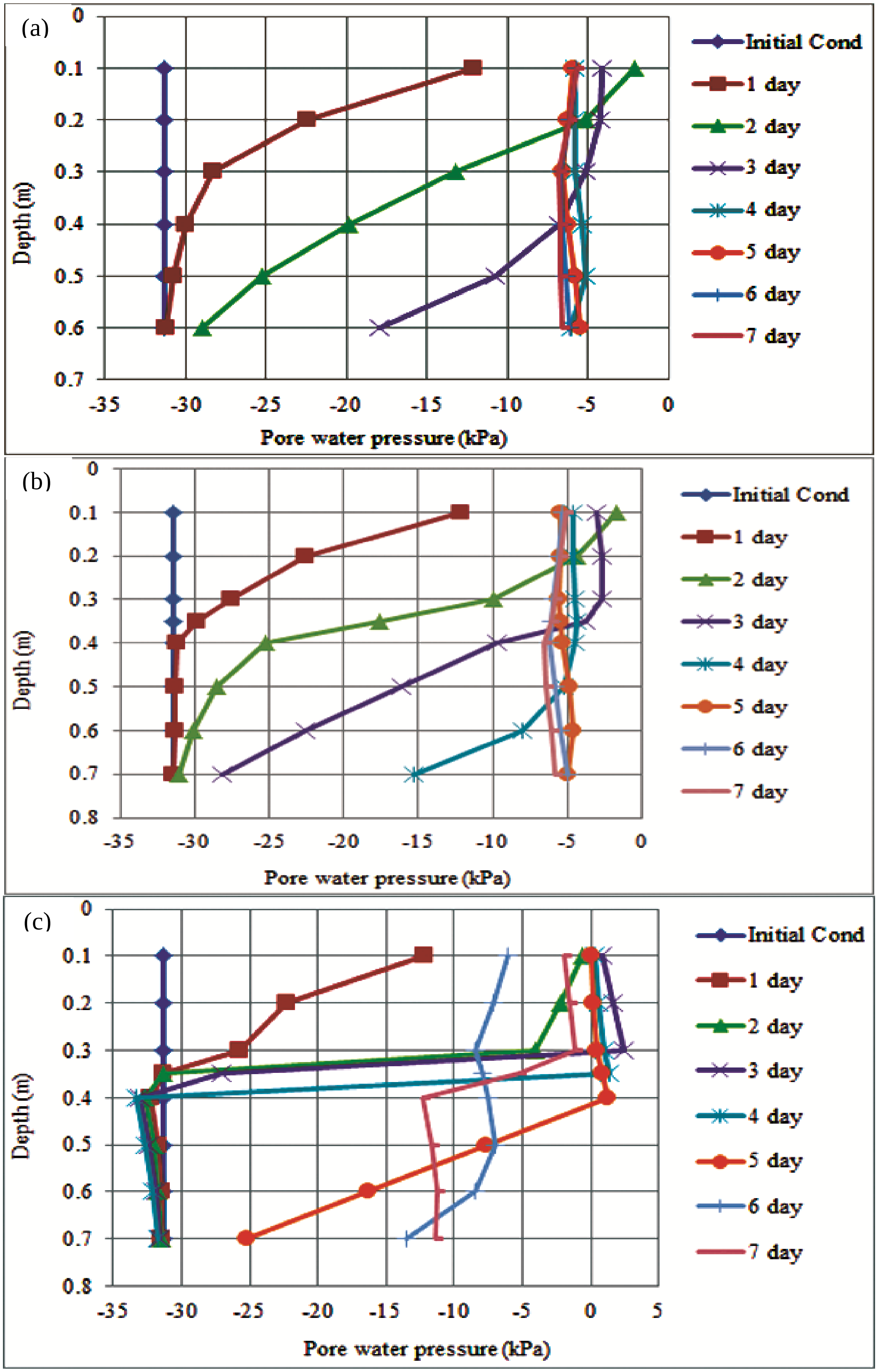

Figure 11 suction distributions with depth due to 7 day rainfall (a) without additional layer (b) With sand (c) with gravel

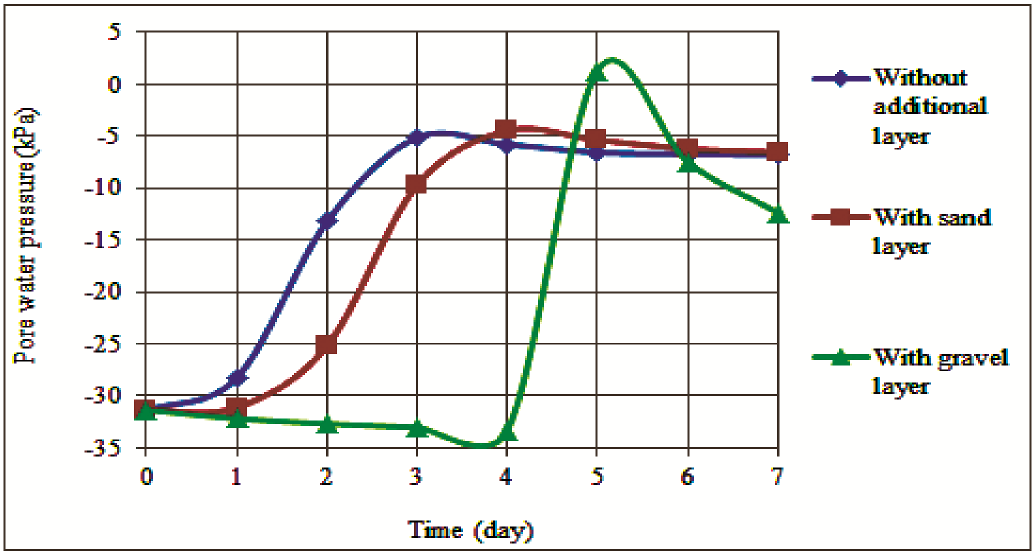

Figure 12 suction distributions with time due to 7 day rainfall

4.0 Conclusions

The performance of fine sand and gravel as unsaturated drainage layer in a capillary barrier system for diverting infiltrated water was studied. The systems were subjected to three different rainfall intensities obtained from IDF curve. Based on the outcome of this study the following conclusions were drawn:

Gravel material is more suitable as unsaturated drainage layer for diverting infiltrated water before breakthrough occurs, and this is because of high capillary break developed between the gravel and upper residual soil layer and due to large particle size contrast between the two materials. For one hour rainfall intensity unsaturated drainage layer is not required because the infiltrated water does not reach interface of the two soil layers and hence the capillary forces in the fine-grained soil layer are capable of retaining the infiltrated water until it later been removed by other processes. In the case of 24 hour and 7 day rainfall the negative pore water pressure changes to positive at certain depth due to accumulation of the infiltrated water at the interface and because large particle size contrast between the fine-grained soil layer and the gravel.

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