

NUMERICAL SIMULATION OF INFILTRATION THROUGH UNSATURATED LAYERED SOIL COLUMN

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Abstract: The effect of changing permeability at the interface for common residual soils, namely Silty Sand, Fine Sand and Gravelly Sand was investigated by conducting numerical simulations of vertical infiltration tests on two layered soil columns of Silty Sand over Fine Sand, and Silty Sand over Gravelly Sand. The results show that water movement across interface between the two layered soils will only occur when the matric suction, $u_a - u_w$, at the interface reached a breakthrough head of 0.4 kPa and 3.5 kPa for Gravelly Sand and Fine Sand, respectively. The pressure heads are defined as the water-entry value, ψ_w , at which the coarser layer became conductive regardless of infiltration rate or the properties of the overlying finer soil layer. The barrier effect in the underlying coarser soil layer was verified from the numerical analysis. The effect was more apparent when the difference in the permeability and the pore-water pressure change across the finer-coarser soil interface were larger.

Keywords: *Permeability, Volumetric water content, Pore water pressure; Soil column*

1 Introduction

The mass instability of soil slopes continue to affect large Malaysian populations each year, in particular at areas of steep terrain that experience prolonged dry periods followed by intense rainfall events. Although slope failures may develop due to human induced factors such as loading or the cutting away of the toe, many failures also occur due to rainfall infiltrating an otherwise stable slope (Campbell, 1974; Johnson and Sitar, 1990). Many researchers observed and analyzed rainfall induced landslides occurred in various terrains due to positive pore pressure generated by intense rainfalls that has the effects of multidirectional seepage into a soil profile (Ng and Shi, 1998; Kasim *et al.*, 1998; Tsaparas *et al.*, 2002). In other words, the infiltration of rainwater into the slopes can cause an increase in pore-water pressure and consequently decrease in the shear strength of the soil forming the slope.

Rainfall induced slope failures often occur at slip plane parallel to the slope surface, especially in areas where residual soil profile has formed over a bedrock interface (Rahardjo *et al.*, 1995). These relatively shallow failures, typically 1 m to 1.5 m deep, are common features in tropical or subtropical climates that experience periods of intense or prolonged rainfall (Lumb, 1975; Wolle and Hachich, 1989).

Residual soil is defined as soil that is formed in-situ by decomposition of parent material under tropical weathering conditions (Sower, 1971; Blight, 1997, Public Works Institute of Malaysia, 1996). Tropical residual soils have some unique characteristics; the most distinct is the microstructure which changes in a gradational manner with depth. The in-situ water content of residual soils is generally greater than its optimum water content for compaction. Their density, plasticity index, and compressibility are likely to be less than the corresponding values for temperate zone soils with comparable liquid limits. On the other hand, their strength and permeability are likely to be greater than those of temperate zone soils with comparable liquid limits. It is also found that permeability of residual soils is considerably affected by the variation in grain size, void ratio, mineral, degree of fissuring and the characteristics of the fissures. Furthermore, Garga and Blight (1997) explained that permeability of some residual soils is strongly controlled by the relict structure of the material in which flow takes place along relict joint, quartz veins, termite or other bio-channels.

The formation of residual soil has resulted in some unique characteristics related to their composition and the environment under which they are developed. This condition can be modeled as layers in the soil profile with different permeability function. Water tends to accumulate in near surface soil layer which consists of finer particles and exhibit lower permeability. An underlying soil, which is coarser, will maximize the barrier effect because the soil is non-conductive until low values of suction head is attained (Hillel and Baker, 1988). With a low pore pressure at the soil interface under unsaturated conditions, the coarser grain soil layer that normally has higher permeability than the finer grain soil layer will limit the downward movement of water and holds the infiltrating water in the finer layer by capillary forces.

The microclimatic conditions are the main factors causing many soil-rock profiles of tropical residual soil to exist in an unsaturated condition. For slopes that are initially unsaturated, rainfall on the slope surface will have dramatically detrimental effect on the stability of residual soil slopes (Gasmo *et al.*, 1999). The pore-water pressure pattern that develops in the soil will occur as a transient process as the infiltrating water moves downward into the soil profile.

When rainfall infiltrates into a soil slope, it will clearly increase the moisture content of the soil above the phreatic surface and hence reduces the suctions in the slope. However, as the water flows downward, it may also result in a rise in the position of the phreatic surface. Such a rise could be the cause of instability of some residual slopes, but as proven by Boosinsuk and Yung (1992) and Rahardjo *et al.* (2000), failure may be induced by direct rainfall, rather than by rising groundwater. Instead, the failures have

been attributed to the migration of wetting front into the slope that strictly related to infiltrated water percolating in unsaturated soil (Lumb, 1975; Sun *et al.*, 1998).

The effect of changing permeability at the interface for common residual soils were studied by performing numerical simulations of vertical infiltration tests on two layered soil columns, namely Silty Sand over Fine Sand, SF and Silty Sand over Gravelly Sand, SG. The principal purpose of the infiltration tests was to investigate the effect of changing permeability under one-dimensional condition by investigating the role of the water-entry values at the interface for layered soil columns. This paper presents the results of the study.

2 Methodology

2.1 Determination of Soil Properties

Three types of soil were used in this study, namely Silty Sand, Fine Sand and Gravelly Sand. The Gravelly Sand, crushed from fresh granite, was light grey to white in color. The Fine Sand was light grey in color and was taken from beach. Silty Sand was a residual silty soil came from a natural local slope.

Classification tests were conducted on each sample following the standard procedures outlined by ASTM D-2487 for which the Unified Soil Classification system, USCS was adopted. Both Fine Sand and Gravelly Sand were categorized as poorly graded sands (SP) while the Silty sand is classified as SM. The saturated permeability (k_s) of the soils was determined from the constant-head permeability test as described in ASTM (1997c) D2434-68.

The relationship between volumetric water content, θ_w , and matric suction of the soils can be represented by soil-moisture retention curve or soil-water characteristic curve (SWCC) which can be obtained by pressure plate test. Furthermore, Fredlund and Xing (1994) prediction method was used to determine the fitting parameters for SWCC and saturated permeability, k_s . The basic properties of the soils are summarized in Table 1 while the SWCC and permeability function curves are shown in Figure 1.

2.2 Numerical Simulation

The numerical simulations of vertical one-dimensional infiltration in two-layer soil columns were performed using the saturated/unsaturated seepage finite element code SEEP/W (Geostudio, 2004). One-dimensional analyses were performed for a 8×20 element mesh (total number of 160 elements and 189 nodes) representing a 1-m deep soil column (Figure 2). The analysis was done for two-layer soil column model of: (1) Silty Sand (700 mm thick) over Fine Sand (300 mm thick) (subsequently referred as SF), and (2) Silty Sand (700 mm thick) over Gravelly Sand (300 mm thick) (subsequently referred as SG).

Table 1: Results of basic properties and soil-water characteristic curve of soils

Description	Symbol	Gravelly Sand	Fine Sand	Silty Sand
Unified Soil Classification System	-	SP	SP	SM
Saturated permeability (m/s)	k_s	4.5×10^{-2}	1.0×10^{-6}	5.0×10^{-7}
Saturated volumetric water content	θ_s	0.378	0.384	0.519
Air-entry value (kPa)	ψ_a	0.11	1.2	10.4
Residual matric suction (kPa)	ψ_r	0.4(0.04)*	3.5(0.35)*	32.5(3.25)*
Residual volumetric water content	θ_r	0.021	0.064	0.115

*value in terms of pressure head (m)

The infiltration was assigned at the top of the column while the bottom of the column was at atmospheric pressure. Hydrostatic condition was selected for the initial condition in all analyses. The simulated rainfall intensity was applied with two different influx boundary conditions of $q = 6.94 \times 10^{-7}$ m/s which is higher than the saturated permeability k_s of Silty Sand and $q = 3.47 \times 10^{-7}$ m/s which is lower than the saturated permeability k_s of Silty Sand for a total period of 6 hours. These precipitation rates were selected to represent severe (60 mm/day) and moderate (30 mm/day) rainfall intensity in Malaysia as suggested by Department of Irrigation and Drainage, Malaysia (2006).

3. Results and Discussion

3.1 General Characteristics

The results of numerical simulation are presented in terms of pressure head vs. depth and volumetric water content vs. depth curves as shown in Figure 3 and 4. It can be seen that the entire process of infiltration was controlled primarily by the less permeable finer grained overlying layer as the wetting front advanced downwards slowly in the upper layer. Hence, the negative pore-water pressure in the upper layer decreased greatly, and even changed to a positive value if the rainfall duration and intensity were large enough as shown in Figures 3 and 4. However, the results also show that the coarser grained underlying layer restricted the development of positive pore-water pressure of the finer layer at the soil interface by allowing water to infiltrate into the lower layer during the infiltration process.

Figure 3(a) shows that the matric suctions in soil column SF gradually decreases at the applied flux $q < k_s$ of Silty Sand and the breakthrough into the coarser layer instantaneously occurred during early stage of infiltration test. The volumetric water

content also decreased significantly at about 0.05 m below the interface. Although the results of soil column SG shows greater increase of pore-water pressure with similar distribution trend in the upper layer, the breakthrough had never occurred as shown by no changes in volumetric water content profile below the interface in Figure 3(b). However, the pore-water pressure at the interface considerably increased near saturation.

Figure 4(a) shows that at the precipitation rate $q > k_s$ of Silty Sand, ponding (or perched water) occurred in the finer upper layer. The ponding occurred after 5.17 hours and 3.83 hours at depth of 0.2 m from the top of the column SF and SG, respectively. The depth was gradually increased in soil column SG where nearly entire upper layer was saturated after 5.83 hours as shown in Figure 4(b). At this stage, the breakthrough into the coarser lower layer occurred as shown by the volumetric water content changes at 0.1 m below the soil interface. The greater depth of water content changes below the interface in soil column SG (0.1 m) as compared to that in soil column SF (0.5 m) could be attributed to the higher value of k_s of Gravelly Sand than that of Fine Sand.

3.2 Effect of changing permeability

The effect of changing permeability at the interface of Silty Sand over Gravelly Sand and Silty Sand over Fine Sand was demonstrated during the infiltration process. The effect could be interpreted from the distribution and change in the pore-water pressure head across the finer-coarser interface during the applied infiltration rates.

Figures 3 and 4 show that the barrier effect during infiltration was less apparent in soil column SF than in soil column SG with respect to change in pore-water pressure head across the finer-coarser soil interface. However, the barrier effect was not sustained for a long time in soil column SF as little breakthrough into the coarser layer instantaneously occurred during early stage of infiltration tests for both influx rates. The temporary barrier effect of changing permeability in restricting the downward movement of water across the column SF is evidenced by the change in pore-pressure heads across the finer-coarser interface.

Figure 4(a) clearly shows that at the precipitation rate of $q > k_s$ of Silty Sand and duration of 5.17 hours, ponding occurred in the upper fine layer of the column at depth of 0.2 m. It demonstrates the barrier effect produced by coarser grained lower layer is impeding downward movement of water in the column.

The effect of the interface was demonstrated by the matric suction developed in soil column SG in response to the infiltration event. As shown in Figure 3(b), when the wetting front reached the interface, the Gravelly Sand did not permit the flux and served as a barrier to downward water movement. The water added at the top of the column remained within the Silty Sand, decreasing the suction heads. There was no observable movement of water past the interface indicating the interface was nonconductive. However, Figure 4(b) shows that eventually the suction head considerably decreased sufficiently to permit water movement into the coarser layer after 5.83 hours lapsed during infiltration.

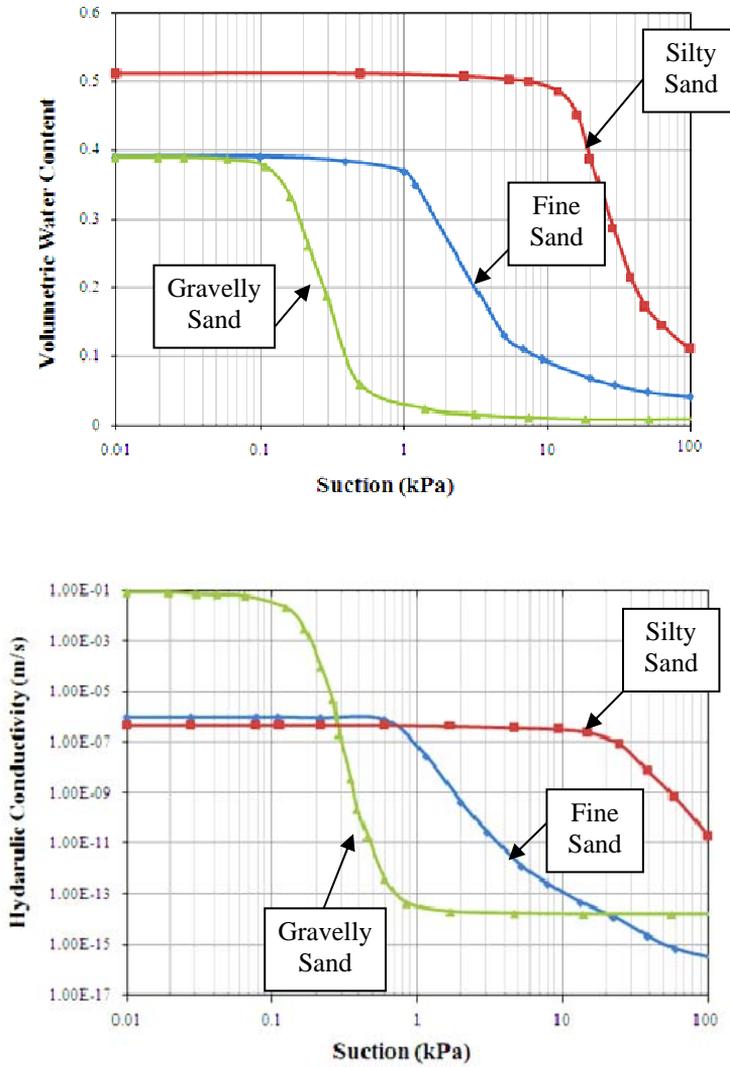


Figure 1: (a) Soil-water characteristic curves and (b) permeability function for Fine Sand, Gravelly Sand and Silty Sand

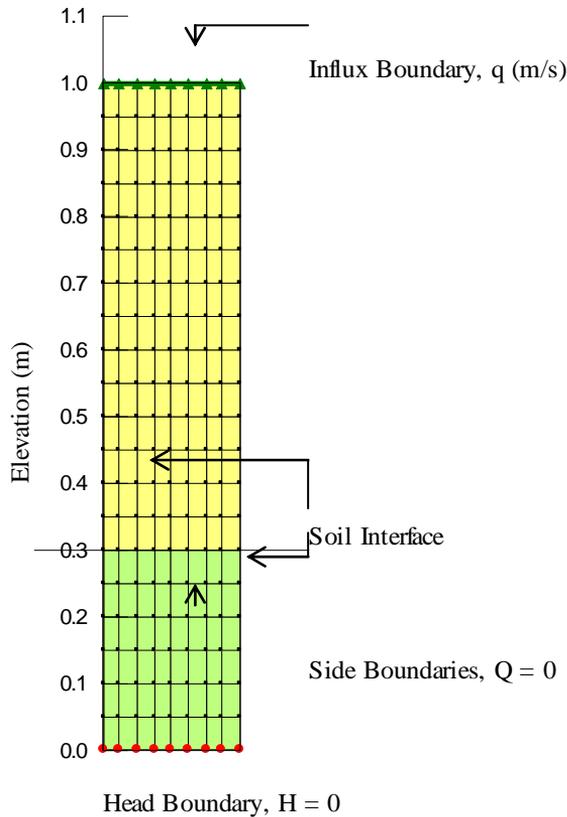


Figure 2: Soil column model simulated for one-dimensional transient analysis

The effect of the change in permeability was more apparent in the case where the coarser layer was Gravelly Sand as compared to the case where the coarse layer was Fine Sand under the same boundary conditions. This is due to the fact that Gravelly Sand has a higher water-entry value than the Fine Sand. In addition, the capillary barrier with the coarser layer of Gravelly Sand was more effective in retaining water than that of the Fine Sand. The water storage in the finer layer appeared to be controlled by the soil type of underlying coarser layer.

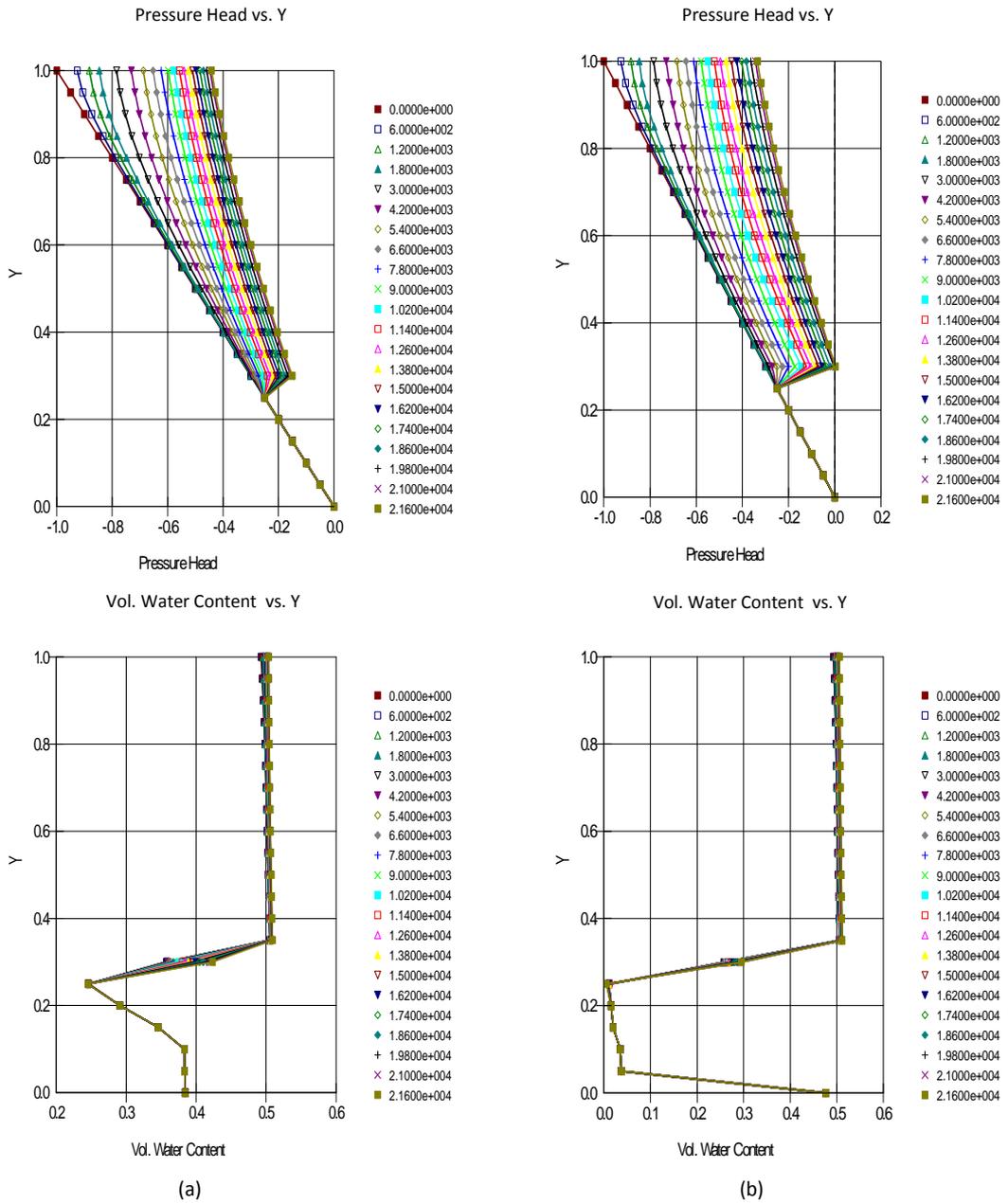


Figure 3: Pore-pressure head profiles and volumetric water content profiles in a rainfall intensity, $q = 3.47 \times 10^{-7}$ m/s (a) soil column SF (b) soil column SG

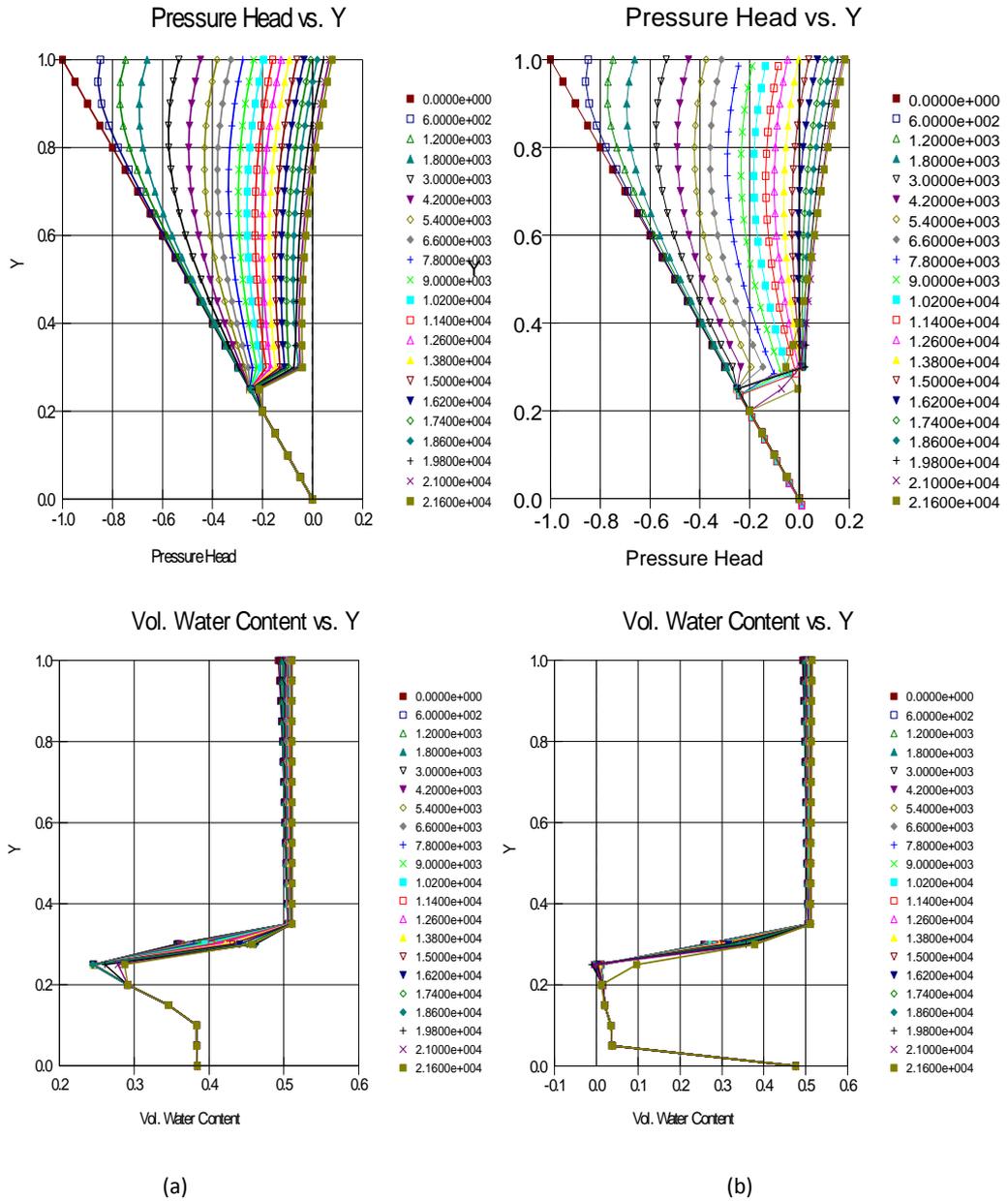


Figure 4: Pore-pressure head profiles and volumetric water content profiles in a rainfall intensity, $q = 6.94 \times 10^{-7}$ m/s (a) soil column SF (b) soil column SG

3.3 Water-entry Value of Underlying Coarse Layer

From the series of infiltration tests on Silty Sand overlying coarser grained soil, the breakthrough into the coarser layer was found to be independent of the precipitation rate. The breakthrough head or water-entry value of the coarser layer is defined as the matric suction at which water first moves into the smaller pores of underlying coarser grained layer (Baker and Hillel 1990). In column SG, water started to breakthrough the finer-coarser interface and entered the underlying Gravelly Sand within the period between of 5.83 hours and 6 hours. Therefore, the matric suction at the finer-coarser interface during this period was the water-entry value of Gravelly Sand, i.e. 0.03 m. However, the water-entry value for the Fine Sand cannot be determined as the breakthrough into the coarser layer instantaneously occurred during early stage of infiltration tests in response to the generated initial condition (at initial condition the pressure head equals to 0.3 m at the interface). The result shows that the water-entry value for the Fine Sand is larger than 0.3m.

Baker and Hillel (1990) suggested that the water entry value of a soil could be approximated to the height of capillary rise of the soil and could be estimated from the inflection point corresponding value of the residual matric suction on drying soil-water characteristic curve. The residual matric suctions of Gravelly Sand and Fine Sand were 0.4 kPa and 3.5 kPa (i.e. 0.04 m and 3.5 m of pressure head), respectively as obtained from Figure 2. The water-entry of Gravelly Sand and Fine Sand as observed in both soil columns were quite close to those determined from soil-water characteristic curve study. This observation support the suggestion of Baker and Hillel (1990) that water-entry value of a soil is nearly equal to the residual matric suction obtained from the drying soil-water characteristic curve of the soil.

4. Conclusion

The numerical analysis showed that the rainfall infiltration through residual soil is affected by the variation of permeability related to the formation of the soil. The effect was more apparent when the difference in the permeability is larger as demonstrated by the SG soil column. Water movement across the interface between two layered SG soil column occurred when the matric suction, $u_a - u_w$ at the interface reached a breakthrough head of 0.4 kPa while for SF soil column, the breakthrough occurred at pressure head of 3.5 kPa. These head values are defined as the water-entry value, ψ_w at which the coarser layer first became conductive regardless of infiltration rate or the properties of the overlying finer soil layer. Furthermore, the barrier effect in the underlying coarser soil layer was verified from the numerical analysis that shows the effect is more apparent when the difference in the permeability and pore-water pressure change across the finer-coarser soil interface are larger.

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