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Figure 5.106 Profiles of volumetric water content in the RLgs-95 column during the rainfall test of IC-RLgs-95R6 (drying process).

Figure 5.107 Drainage velocity in the RLgs-95 column during the rainfall test of IC-RLgs-95R6.
5.3. Numerical Simulations

Numerical simulations on the tests of drawdown of water table and rainfall were performed on the capillary barrier models using the initial and boundary conditions being applied in the laboratory experiments. Section 5.3.1 presents the results of numerical simulation on the RGgs-50 column. Subsequently, the results of numerical simulations on the RMgs-75 column are presented in Section 5.3.2. Lastly, results of numerical simulations on the RLgs-95 column are presented in Section 5.3.3.

The term of NS, such as in the NS-RGgs-50Dr and the NS-RGs-50R1, refers to numerical simulation, while the terms of Dr and the R1 indicate drawdown test and rainfall test, respectively.

5.3.1. Numerical Simulations on RGgs-50 column

The results of numerical simulations on the RGgs-50 column are presented in this section. The results of numerical simulation of drawdown test are shown in Figure 5.108 and Figure 5.109, while the results of numerical simulations on the rainfall tests are shown in Figure 5.110 to Figure 5.117.
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Figure 5.109 Profiles of volumetric water content in the RGgs-50 column in the numerical simulation of drawdown test of NS-RGgs-50Dr.

Figure 5.110 Profiles of pore-water pressures in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R1.
Figure 5.111 Profiles of volumetric water content in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R1.

Figure 5.112 Profiles of pore-water pressures in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R2.
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Figure 5.113 Profiles of volumetric water content in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R2.

Figure 5.114 Profiles of pore-water pressures in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R3.
Figure 5.115 Profiles of volumetric water content in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R3.

Figure 5.116 Profiles of pore-water pressures in the RGgs-50 column in the numerical simulation of rainfall test of NS-RGgs-50R4.
Numerical Simulations on RMgs-75 column

The results of numerical simulations on the RMgs-75 column are presented in this section. The results of numerical simulation of the drawdown test are shown in Figure 5.118 and Figure 5.119, while the results of numerical simulations of the rainfall tests are shown in Figure 5.120 to Figure 5.129.
Figure 5.118 Profiles of pore-water pressures in the RMgs-75 column in the numerical simulation of drawdown test of NS-RMgs-75Dr.

Figure 5.119 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of drawdown test of NS-RMgs-75Dr.
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Figure 5.120 Profiles of pore-water pressures in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R1.

Figure 5.121 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R1.
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Figure 5.122 Profiles of pore-water pressures in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R2.

Figure 5.123 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R2.
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Figure 5.124 Profiles of pore-water pressures in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R3.

Figure 5.125 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R3.
Figure 5.126 Profiles of pore-water pressures in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R4.

Figure 5.127 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R4.
Figure 5.128 Profiles of pore-water pressures in the numerical simulation of rainfall test of NS-RMgs-75R5.

Figure 5.129 Profiles of volumetric water content in the RMgs-75 column in the numerical simulation of rainfall test of NS-RMgs-75R5.
5.3.3. Numerical Simulations on RLgs-95 column

Results of numerical simulations on the RLgs-95 column are presented in this section. The pore-water pressure profiles obtained from the numerical simulations are shown in Figures 5.130, 5.132, 5.134, 5.136, and 5.138, while the volumetric water content profiles are shown in Figures 5.131, 5.133, 5.135, 5.137, and 5.139.

![Figure 5.130 Profiles of pore-water pressures in the RLgs-95 column in the numerical simulation of drawdown test of NS-RLgs-95Dr.](image1)

![Figure 5.131 Profiles of volumetric water content in the RLgs-95 column in the numerical simulation of drawdown test of NS-RLgs-95Dr.](image2)
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Figure 5.132 Profiles of pore-water pressures in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R1.

Figure 5.133 Profiles of volumetric water content in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R1.
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Figure 5.134 Profiles of pore-water pressures in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R2.

Figure 5.135 Profiles of volumetric water content in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R2.
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Figure 5.136 Profiles of pore-water pressures in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R3.

Figure 5.137 Profiles of volumetric water content in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R3.
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Figure 5.138 Profiles of pore-water pressures in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R4.

Figure 5.139 Profiles of volumetric water content in the RLgs-95 column in the numerical simulation of rainfall test of NS-RLgs-95R4.
5.4. Comparison of Numerical Simulations and Experimental Data

Results of the numerical simulations and the laboratory experiments are compared and presented in this section. Comparison of the results of the numerical simulations and laboratory experiments during the drawdown of water table are presented in Section 5.4.1, while the results of the numerical simulations and laboratory experiments during rainfall tests are presented in Section 5.4.2.

5.4.1. Tests of drawdown of water table

Comparison of pore-water pressure head profiles obtained from numerical simulations and the laboratory experiments are presented in Section 5.4.1.1, while comparison of volumetric water content profile obtained from numerical simulations and the laboratory experiments are presented in Section 5.4.1.2.

5.4.1.1. Pore-water pressure head profiles

Results of comparison of the pore-water pressure head profiles obtained from the numerical simulations and the laboratory experiments are shown in Figure 5.140 to Figure 5.145.
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Figure 5.140 Comparison of the pore-water pressure head profiles in the RGgs-50 column during drawdown of water table of the IC-RGgs-50Dr and the NS-RGgs-50Dr (1 of 2).
Figure 5.141 Comparison of the pore-water pressure head profiles in the RGgs-50 column during drawdown of water table of the IC-RGgs-50Dr and the NS-RGgs-50Dr (2 of 2).
Figure 5.142 Comparison of the pore-water pressure head profiles in the RMgs-75 column during drawdown of water table of the IC-RMgs-75Dr and the NS-RMgs-75Dr (1 of 2).
Figure 5.143 Comparison of the pore-water pressure head profiles in the RMgs-75 column during drawdown of water table of the IC-RMgs-75Dr and the NS-RMgs-75Dr (2 of 2).
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Figure 5.144 Comparison of the pore-water pressure head profiles in the RLgs-95 column during drawdown of water table of the IC-RLgs-95Dr and the NS-RLgs-95Dr (1 of 2).
Figure 5.145 Comparison of the pore-water pressure head profiles in the RLgs-95 column during drawdown of water table of the IC-RLgs-95Dr and the NS-RLgs-95Dr (2 of 2).
5.4.1.2. Volumetric water content profiles

Results of comparison of the volumetric water content profiles obtained from the numerical simulations and the laboratory experiments are shown in Figure 5.146 to Figure 5.151.

**Figure 5.146** Comparison of the volumetric water content profiles in the RGgs-50 column during drawdown of water table of the IC-RGgs-50Dr and the NS-RGgs-50Dr (1 of 2).
Figure 5.147 Comparison of the volumetric water content profiles in the RGgs-50 column during drawdown of water table of the IC-RGgs-50Dr and the NS-RGgs-50Dr (2 of 2).
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Figure 5.148 Comparison of the volumetric water content profiles in the RMgs-75 column during drawdown of water table of the IC-RMgs-75Dr and the NS-RMgs-75Dr (1 of 2).
Figure 5.149 Comparison of the volumetric water content profiles in the RMgs-75 column during drawdown of water table of the IC-RMgs-75Dr and the NS-RMgs-75Dr (2 of 2).
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Figure 5.150 Comparison of the volumetric water content profiles in the RLgs-95 column during drawdown of water table of the IC-RLgs-95Dr and the NS-RLgs-95Dr (1 of 2).
Figure 5.151 Comparison of the volumetric water content profiles in the RLgs-95 column during drawdown of water table of the IC-RLgs-95Dr and the NS-RLgs-95Dr (2 of 2).
5.4.2 Rainfall tests

Comparison of pore-water pressure head profiles obtained from numerical simulations and the laboratory experiments are presented in Section 5.4.2.1, while comparison of volumetric water content profile obtained from numerical simulations and the laboratory experiments are presented in Section 5.4.2.2.

5.4.2.1. Pore-water pressure head profiles

Results of comparison of the pore-water pressure head profiles obtained from the numerical simulations and the laboratory experiments are shown in Figure 5.152 to Figure 5.163.
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Figure 5.152 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R1 and the NS-RGgs-50R1 (1 of 2).
Figure 5.153 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50Rl and the NS-RGgs-50Rl (2 of 2).
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Figure 5.154 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R2 and the NS-RGgs-50R2 (1 of 2).
Figure 5.155 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall test of the IC-RGgs-50R2 and the NS-RGgs-50R2 (2 of 2).
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Figure 5.156 Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75RI and the NS-RMgs-75RI (1 of 2).
Figure 5.157 Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R1 and the NS-RMgs-75R1 (2 of 2).
Figure 5.158 Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R2 and the NS-RMgs-75R2 (1 of 2).
Figure 5.159 Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R2 and the NS-RMgs-75R2 (2 of 2).
Figure 5.160 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R1 and the NS-RLgs-95R1 (1 of 2).
Figure 5.161 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R1 and the NS-RLgs-95R1 (2 of 2).
Figure 5.162 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R2 and the NS-RLgs-95R2 (1 of 2).
Figure 5.163 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R2 and the NS-RLgs-95R2 (2 of 2).
5.4.2.2. Volumetric water content profiles

Results of comparison of the volumetric water content profiles obtained from the numerical simulations and the laboratory experiments are shown in Figure 5.164 to Figure 5.175.

Figure 5.164 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R1 and the NS-RGgs-50R1 (1 of 2).
Figure 5.165 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R1 and the NS-RGgs-50R1 (2 of 2).
Figure 5.166 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R2 and the NS-RGgs-50R2 (1 of 2).
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Figure 5.167 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall test of the IC-RGgs-50R2 and the NS-RGgs-50R2 (2 of 2).
Figure 5.168 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R1 and the NS-RMgs-75R1 (1 of 2).
Figure 5.169 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R1 and the NS-RMgs-75R1 (2 of 2).
Figure 5.170 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R2 and the NS-RMgs-75R2 (1 of 2).
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Figure 5.171 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R2 and the NS-RMgs-75R2 (2 of 2).
Figure 5.172 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R1 and the NS-RLgs-95R1 (1 of 2).

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Figure 5.173 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R1 and the NS-RLgs-95R1 (2 of 2).
Figure 5.174 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R2 and the NS-RLgs-95R2 (1 of 2).
Figure 5.175 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R2 and the NS-RLgs-95R2 (2 of 2).
Chapter 6
Discussions

Results obtained during this study are discussed in detail in this chapter. Section 6.1 presents discussions on the assessment of the laboratory infiltration tests. Section 6.2 presents discussions on the comparison between the numerical simulations results and the experimental data. Effects of modification of the residual soil are discussed in Section 6.3.

6.1. Assessment of the Laboratory Infiltration Tests

Factors related to the laboratory infiltration tests are discussed in this section. Section 6.1.1 presents discussions on the barrier effect of the capillary barriers. Section 6.1.2 presents discussions on the maximum negative pore-water pressure developed in the capillary barrier models. Section 6.1.3 presents discussions on the effectiveness of the tensiometer-transducer system in measuring the pore-water pressure head of the soils. The effectiveness of the TDR system in measuring the volumetric water content of the soils is discussed in Section 6.1.4. Section 6.1.5 presents discussions on the effectiveness of the filter cloth in preventing soil migration. Lastly, effects of the rainfall intensity and duration on the capillary barrier models are discussed in Section 6.1.6.

6.1.1. Barrier effect of the capillary barriers

In this study, capillary barrier models are constructed mainly in order to impede the downward movement of water infiltration into the underlying protected system based on the contrast in the permeability of the fine-grained layer and the coarse-grained layer under unsaturated conditions. The barrier effect of the capillary
barriers developed in this study can be observed from the distribution of the pore-water pressures, especially in the lower part of the fine-grained layer and in the upper part of the coarse-grained layer during the rainfall tests.

A rainfall test conducted on the IC-RGgs-50R4 (Figure 5.40 and Figure 5.41) presents a special case where a capillary barrier effect can be clearly viewed. A rainfall intensity of 9 mm/h was applied for 2 hours (Table 4.1) on the top of the RG-50 overlying the gravelly sand. Figure 5.40 shows that during the early stage of the wetting process, the pore-water pressure head in the upper part of the fine-grained layer increased rapidly. As time elapsed, the pore-water pressure head in the middle and lower part of the fine-grained layer also increased simultaneously. Since the applied rainfall intensity and the saturated permeability of the fine-grained layer were relatively high, the infiltrating water reached the soil interface at $t = 70$ min, which was indicated by the increase in the pore-water pressure head or the movement of the profile of pore-water pressure head from left to right. However, during $t = 70$ min (i.e., the time when the wetting front reached the soil interface) until $t = 2h$ (i.e., the time when the rainfall was stopped) water did not move down to the coarse-grained layer as the pore-water pressure head in the upper part of the gravelly sand remained constant. It is obvious that there was a mechanism that impeded the downward movement of water so that water could not infiltrate into the coarse-grained layer. The break in the water flow was caused by the extremely low permeability of the gravelly sand. However, since there was no other ways for water to flow, the capillary break did not last longer. In the following period from $t = 2h$ to $t = 3h$, water started to enter the upper part of the coarse-grained layer (Figure 5.41) as indicated by the increase in the pore-water pressure head in the upper part of the coarse-grained layer from -0.09m to -0.01m. As more water filled the pores of the soil, the permeability of the gravelly sand increased and water started to flow downward to the entire coarse-grained layer.

During the period of $t = 2h$ until $t = 6h$, water still infiltrated downward from the upper part of the fine-grained layer to the coarse-grained layer (Figure 5.41). The fine-grained layer underwent a drying process, while the coarse-grained layer was
still undergoing a wetting process. Thus, the profiles of pore-water pressure head in the fine-grained layer moved to the left, while the profiles of pore-water pressure head in the coarse-grained layer moved to the right. After $t = 6h$, the infiltrating water started to drain out from the bottom of the coarse-grained layer, causing the pore-water pressure in the coarse layer to decrease and the pore-water pressure head profiles moved to the left until an ultimate negative pore-water pressure head profile was established.

Figures 5.54 and 5.55 show another ideal case of the barrier effect of capillary barriers as demonstrated by the RMgs-75 column. A rainfall test of IC-RMgs-75R2 was conducted on the RMgs-75 column with a rainfall intensity of 1.3mm/h and a rainfall duration of 6h. Figure 5.54 shows that during the application of the rainfall, the pore-water pressure head of the fine-grained layer increased and the profiles of the pore-water pressure head moved to the right progressively. As time elapsed, more water infiltrated through the RM-75 and the wetting front reached the interface of the RM-75 and the gravelly sand at $t = 2h$. During $t = 2h$ until $t = 6h$, the wetting front was still at the interface of the RM-75 and the gravelly sand. Subsequently, water break through into the gravelly sand occurred around $t = 4h$ and $t = 6h$, as indicated by the increase in the pore-water pressure head of the upper part of the gravelly sand from -0.05m to -0.01m. Once the breakthrough occurred, the permeability of the gravelly sand increased progressively causing more water to infiltrate into the gravelly sand.

Unlike the RGgs-50 column and RMgs-75 column, the RLgs-95 column showed the barrier effect of a capillary barrier in a different way. Figure 5.83 and Figure 5.84 show a rainfall test of IC-RLgs-95R2 conducted on the RLgs-95 column with a rainfall intensity of 9.7mm/h for a duration of 2h. In the early stage of the rainfall application, the pore-water pressure head in the upper part of the RL-95 increased drastically. Even though the pore-water pressure head in the upper part of the RL-95 increased drastically and the wetting front reached the interface of the RL-95 and the gravelly sand, the pore-water pressure head in the upper part of the gravelly sand.
sand remained constant up to $t = t_0$, after which the pore-water pressure head of the gravelly sand increased progressively and the breakthrough occurred.

Another way to see the barrier effect of the capillary barriers is through the distribution of pore-water pressure at the interface of the fine-grained layer and the coarse-grained layer. In each capillary barrier model, a tensiometer-transducer system with a ceramic tip was installed at the interface of the fine-grained layer and the coarse-grained layer in order to capture the change in the pore-water pressure head during infiltration tests.

Results of the drawdown tests and the rainfall tests, particularly in the RGgs-50 column and RMgs-75 column (Figures 5.22 and 5.46), showed that the pore-water pressure head profile of the gravelly sand was nearly vertical from $z = 0.05m$ to $z = 0.45m$, after which the profile tended to incline to the right and the pore-water pressure head in the upper part of the gravelly sand was slightly lower than the pore-water pressure head at the soil interface. This observation can be explained by the changes in the hydraulic properties of the fine-grained layer and the coarse-grained layer.

In the initial stage of the drawdown test, the matric suction of the fine-grained layer (i.e., RG-50 or RM-75) and the coarse-grained layer (i.e., gravelly sand) increased, causing the volumetric water content of the soils to decrease rapidly. The decrease in the volumetric water content was accompanied by the decrease in the permeability of the soils, where the permeability of the gravelly sand decreased faster and larger than the permeability of the fine-grained layer. The pore-water pressure head profile of the gravelly sand then reached the equilibrium condition in short time (e.g., 20min in the IC-RGgs-50Dr), while the pore-water pressure head profile of the fine-grained layer was still moving toward the hydrostatic, suggesting that the water in the fine-grained layer was still infiltrating downward toward the gravelly sand. When the equilibrium profile of the pore-water pressure head in the gravelly sand had developed, the permeability of the gravelly sand was extremely low. Since the fine-grained layer was still conductive enough for water infiltration,
while the permeability of the gravelly sand was extremely low, water that infiltrated from the fine-grained layer was not able to move downward freely toward the gravelly sand. As a consequence, the infiltrating water was impeded at the interface of the fine-grained layer and the coarse-grained layer. In other words, water accumulated at the interface of the fine-grained layer and the coarse-grained layer as a result of the low permeability of the gravelly sand under unsaturated conditions. The observation of the “entrapped water” at the interface of the fine-grained layer and the coarse-grained layer occurred not only in the drawdown test but also during drying processes of the rainfall tests.

6.1.2. Maximum negative pore-water pressures
Tests of rapid drawdown of water table conducted on the IC-RGgs-50Dr, IC-RMgs-75, and IC-RLgs-95 (Figures 5.22, 5.46, and 5.75) were started from the hydrostatic positive pore-water pressure (i.e., total head, which is the pressure head plus the elevation head, equals to one throughout the soil column). Once the drawdown test was started, the total head in the soil column started to vary from positive values in the upper part of the soil column to zero at \( z = 0 \) (i.e., where the water table was maintained throughout the test). This suggested that water was flowing downward. Theoretically, the downward flow of water continued until the hydrostatic profile of negative pore-water pressure head (i.e., total head equals to zero throughout the soil column) was established, after which there would be no water flow occurred in the soil column.

Results of the drawdown tests showed that the hydrostatic profile of negative pore-water pressure head only developed in the IC-RLgs-95Dr (Figure 5.75). Both the fine-grained layer (i.e., RL-95) and the coarse-grained layer (i.e., gravelly sand) reached the hydrostatic profile of negative pore-water pressure head in less than 12h. On contrary, the hydrostatic profile of negative pore-water pressure head of the gravelly sand practically could not develop in the IC-RGgs-50Dr and the IC-RMgs-75Dr, even though the tests were ended after 72h (Figure 5.22 and Figure 5.46).
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The maximum negative pore-water pressure head developed in the infiltration column during the drying process can be related to the SWCCs and the permeability functions of the soils. In the initial stage of the drawdown test, the volumetric water content and the permeability of the soil were relatively high and, thus, water could flow easily. As time elapsed, the matric suction increased and the permeability of the fine-grained layer and the coarse-grained layer decreased. Since the pores in the gravelly sand were much larger than the pores in the fine-grained layers (i.e., RG-50 and the RM-75), the volumetric water content of the gravelly sand decreased faster than that of the fine-grained layers. When the residual volumetric water content of the gravelly sand was approached, the permeability of the gravelly sand in the IC-RGgs-50Dr and the IC-RMgs-75Dr decreased to an extremely low value and the water phase became increasingly discontinuous, leaving isolated pockets of water that were bounded around soil particles. Since evaporation was prevented during the test, there was no other mechanism for the pore-water redistribution, causing the isolated pockets of water in the gravelly sand to be “locked in” at the pore-water pressure just before the water phase became discontinuous (Barbour and Yanful, 1994). Observations of the “static” nonequilibrium pressures were also reported by several researchers (e.g., Choo and Yanful, 2000; Yang, 2002) based on their column studies.

Furthermore, the maximum negative pore-water pressure developed in the soil column during a drying process was approximately the same as the matric suction corresponding to the residual volumetric water content (or the residual matric suction), after which a nearly vertical profile developed throughout the soil column (Barbour and Yanful, 1994; Yang, 2002). In the IC-RGgs-50Dr, the residual matric suction of the gravelly sand as obtained from the SWCC test was about 0.5kPa (i.e., equal to -0.05m pore-water pressure head) (Figure 5.6 and Table 5.5). This was comparable to the maximum negative pore-water pressure of the gravelly sand developed at \( z = 0.05m \) above the water table, which was approximately -0.05m (Figure 5.22). From this maximum negative pore-water pressure point, a nearly vertical profile then developed throughout the gravelly sand until it reached the interface. The continuity of pore-water pressure required the pore-water pressure at
the uppermost of the gravelly sand to be equal to the pore-water pressure at the lowermost of the RG-50. Therefore, the pore-water pressure head developed at the lowermost of the RG-50 started approximately from -0.05m. The result of the SWCC test showed that the residual matric suction of the RG-50 was 8kPa (i.e., equal to -0.8m pore-water pressure head). Since the height of the RG-50 in the RGgs-50 column was only 0.5m, the maximum pore-water pressure head developed in the upper part of the RG-50 became -0.55m (i.e., -0.05m plus -0.5m).

Similar characteristic was also observed in the RMgs-75 column during drying process. In case of the IC-RMgs-75Dr (Figure 5.46), the maximum negative pore-water pressure head of the gravelly sand developed in the infiltration column was also around -0.05m, which was comparable to the residual matric suction of the gravelly sand obtained from the SWCC test as previously mentioned for the IC-RGgs-50Dr. The continuity of the pore-water pressure led the uppermost layer of the gravelly sand to have the same pore-water pressure head as the lowermost layer of the RM-75. Result of the SWCC test (Table 5.7) showed that the residual matric suction of the RM-75 was 7kPa (i.e., equal to -0.7m pore-water pressure head). Since the total thickness of the RM-75 in the IC-RMgs-75Dr was only 0.5m, thus, the maximum negative pore-water pressure head of the RM-75 in the infiltration column was only -0.55m.

The maximum negative pore-water pressure of the gravelly sand developed in the IC-RLgs-95Dr (Figure 5.75) was much higher than those of the gravelly sand developed in the IC-RGgs-50Dr (Figure 5.22) and in the IC-RMgs-75Dr (Figure 5.46), although the same gravelly sands were used as the coarse-grained layers of those capillary barrier models. One of the most possible explanations for this phenomenon is because the hydraulic properties of the gravelly sand in the IC-RLgs-95Dr changed during the drawdown test. As previously mentioned, the RL-95 was a soil mixture consisted of 95% residual soil and 5% lime. During the saturation of the RLgs-95 column (i.e., in the upward infiltration test), the lime was dissolved into the water. Once the drawdown test was started, water in the form of the solution flowed downward into the gravelly sand, allowing the lime to be
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distributed particularly in the upper part of the gravelly sand. As time elapsed, the permeability of the gravelly sand decreased to an extremely low value and the lime was deposited in the gravelly sand. The deposited lime, then, caused the changes in the hydraulic properties of the gravelly sand. The changes in the hydraulic properties of the gravelly sand could be shown by the increase in the residual matric suction as measured by the tensiometer particularly in the upper part of the gravelly sand (e.g., Figure 5.75) and the increase in the volumetric water content as measured by the TDR system (e.g., Figure 5.76). As the residual matric suction the gravelly sand in the RLgs-95 increased up to 5kPa (or may be more, Figure 5.8), the continuity of the pore-water pressure at the soil interface required the pore-water pressure head at the lowermost layer of the RL-95 to be equal to -0.5m. Since the total thickness of the RL-95 in the IC-RLgs-95Dr was only 0.5m and the residual matric suction of the RL-95 was up to 62.8kPa (Table 5.8), the maximum negative pore-water pressure head of the RL-95 developed at the end of the test became -1m.

6.1.3. Effectiveness of the tensiometer-transducer system

A proper installation of ceramic tips of the tensiometer-transducer systems is required to ensure the accuracy of the pore-water pressure head readings. The ceramic tip of the tensiometer-transducer system should be fully saturated and should be well calibrated before use. In addition, the principle of the tensiometer requires the ceramic tip of a tensiometer-transducer system to be kept in good contact with the surrounding soils.

In general, the performance of the tensiometer-transducer systems used in this study was good. The devices could capture accurately the changes in the pore-water pressure head during the steady state (i.e., during the upward infiltration tests) and transient process (i.e., during drawdown of water table and rainfall tests) of water infiltration. Figures 6.1(a) and 6.1(b) show the pore-water pressure head readings during two subsequent drawdown tests of water table in RLgs-95 column. The initial conditions and test procedures were set to be the same for both experiments. The results showed that small discrepancies of pore-water pressure head readings
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were observed in the fine-grained layer and the coarse-grained layer, particularly at \( t = 1h \) and \( t = 2h \), suggesting that two similar infiltration processes may not end up with exactly the same results. This helps to explain the small discrepancy observed between the numerical simulation results and the laboratory experimental data.

Figure 6.1 Comparison of the pore-water pressure head profiles in the RLgs-95 column during tests of drawdown of water table (IC-RLgs-95R1 and IC-RLgs-95R2).
6.1.4. Effectiveness of the TDR system

Results of the infiltration tests conducted during this study showed that, in general, the TDR system could measure the changes in the volumetric water contents of the fine-grained layer and coarse-grained layer in the infiltration columns. Figures 6.2, 6.3, and 6.4 show verification results of the volumetric water contents measured by TDR system and by oven-drying. Measurements of the volumetric water contents by TDR system were performed during each preparation stage of the infiltration tests under saturated condition (S=1), where the waveguides of the TDR system were submerged in the column filled with water only, and at the end of each series of infiltration tests under unsaturated condition (S<1). In order to verify results of the TDR system readings, at the end of each series of infiltration tests, the volumetric water contents of soils were also measured by oven-drying method. The verification results show that there were reasonably agreements between the volumetric water contents measured by the TDR system and those measured by oven-drying method, suggesting that the TDR system is a valuable device for measuring volumetric water contents of soils.

Figure 6.2 Comparison of the volumetric water contents in the RGgs-50 column.
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Figure 6.3 Comparison of the volumetric water contents in the RMgs-75 column.

![Graph showing comparison of volumetric water contents in RMgs-75 column]

Figure 6.4 Comparison of the volumetric water contents in the RLgs-95 column.

![Graph showing comparison of volumetric water contents in RLgs-95 column]
6.1.5. Effectiveness of the filter cloth

During soil compaction in the infiltration column, a filter cloth was placed at the interface of the fine-grained layer and the coarse-grained layer. It was meant to prevent migration of fine-grained contents of the fine-grained layer into the coarse-grained layer. In the capillary barrier models of the RGgs-50 and the RMgs-75, the filter cloths were quite effective in preventing soil migration since there was no fine-grained contents accumulated in the coarse-grained as observed during the tests. In addition, results of the volumetric water content measurements during all infiltration tests (for example see Figure 5.23 for the RGgs-50 column and Figure 5.47 for the RMgs-75 column) showed that there were sharp contrasts in the volumetric water contents of the fine-grained layers and the coarse-grained layers under the same matric suction as also observed from the Tempe cell and Pressure plate test results.

In contrast to the observations in the capillary barrier models of the RGgs-50 and the RMgs-75, lime migration occurred in the RLgs-95 column, suggesting the ineffectiveness of the filter cloth in preventing lime migration in the form of solutions. The visual observation performed at the end of the infiltration tests showed that a substantial amount of lime was accumulated particularly in the upper part of the gravelly sand. The visual observation was supported by the results of pore-water pressure and volumetric water content measurements. The residual matric suctions of the gravelly sand increased significantly, causing the hydrostatic profile of negative pore-water pressure head to develop throughout the soil column (for example see Figure 5.75). In addition, the volumetric water contents of the fine-grained layer and the upper part of the coarse-grained layer measured by the TDR system during the infiltration tests were relatively continuous, suggesting that the TDR system measured two soils with similar volumetric water contents (for example see Figure 5.76).
6.1.6. Effect of the rainfall intensity and duration

Rainfall intensities ranging from 1.1mm/h to 9.9mm/h with durations of 2h to 12h were applied to the capillary barrier models. Figure 6.5 shows the effect of rainfall intensity on the changes of the pore-water pressure heads in the RLgs-95 columns during rainfall tests. Rainfall intensities of 3.0mm/h and 6.1mm/h were applied to the top of the RLgs-95 column (i.e, in the tests of IC-RLgs-95R2 and IC-RLgs-95R6).

The pore-water pressure head profiles showed that at t = 10min, the pore-water pressure head at the upper part of the RL-95 in the test of IC-RLgs-95R2 reached -0.15m, while at the same time step, the pore-water pressure head at the upper part of the RL-95 in the test of IC-RLgs-95R6 was only -0.85m. Furthermore, at t = 30min, the pore-water pressure head at the upper part of the RL-95 in the test of IC-RLgs-95R2 increased to -0.1m, while the pore-water pressure head at the upper part of RL-95 in the test of IC-RLgs-95R6 was still -0.5m. Thus, it is clearly shown from

![Figure 6.5 Comparison of the pore-water pressure head profiles in the RLgs-95 columns during wetting processes of rainfall tests (IC-RLgs-95R2 and IC-RLgs-95R6), showing the effect of rainfall intensity on the movement of the profiles.](image-url)
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the results of rainfall tests that the rate of the change in the pore-water pressure head of the fine-grained layers was strongly affected by the rainfall intensity. The rainfall test with a higher intensity resulted in a faster increase in the pore-water pressure head.

The results of these rainfall tests showed that the pore-water pressure head remained negative throughout the soil columns. This might be due to the fact that the rainfall intensities applied in these rainfall tests were smaller than the coefficient of permeability at saturation, \( k_s \), of the fine-grained layers (Table 4.1). There was no ponding of water at the soil surface observed during all rainfall tests. Since the coefficient of permeability at saturation, \( k_s \), of the soil was higher than the applied rainfall intensities, all of the rainwater infiltrated into the soil column.

![Graph showing pore-water pressure head profiles](image)

**Figure 6.6** Comparison of the pore-water pressure head profiles in the RMgs-75 columns during wetting processes of rainfall tests (IC-RMgs-75R2 and IC-RMgs-75R3), showing the effect of rainfall duration on the movement of the profiles.

In addition to the rainfall intensity, rainfall duration also influenced infiltration process of the capillary barrier models. For example, Figure 6.6 shows results of the rainfall tests conducted on the RMgs-75 capillary barrier model. Rainfall intensities
of 1.3mm/h for 6h and 0.9mm/h for 12h were applied to the top of the RMgs-75 columns in the tests of IC-RMgs-75R2 and the IC-RMgs-75R3, respectively. Under a comparable rainfall intensity, the pore-water pressure head in the upper part of RM-75 in the test of IC-RMgs-75R3 increased up to -0.1m at t = 9h, while the pore-water pressure head in the upper part of the RM-75 in the test of IC-RMgs-75R2 only reached -0.25m at the end of the rainfall application. The longer rainfall duration resulted in a higher pore-water pressure head developed in the soil column.

6.2. Comparison of Numerical Simulation Results and Experimental Data

Results of infiltration tests on the capillary barrier models obtained from laboratory tests and numerical simulations are compared and discussed in this section. Section 6.2.1 presents discussions on the results obtained from the tests of drawdown of water table. Meanwhile, results of the rainfall tests are discussed in Section 6.2.2.

6.2.1. Comparison of the results of rapid drawdown of water table

The pore-water pressure head profiles obtained during laboratory tests of rapid drawdown of water table and from the numerical simulations are compared and discussed in Section 6.2.1.1. Subsequently, Section 6.2.1.2 presents discussions on the comparison of the volumetric water content profiles obtained during laboratory tests of rapid drawdown of water table and from the numerical simulations.

6.2.1.1. Pore-water pressure head profiles

Results of comparison of the pore-water pressure head profiles obtained from the numerical simulations and the laboratory experiments are presented in Section 5.4.1.

In the capillary barrier models of the RGgs-50 and the RMgs-75 (Figure 5.140 to Figure 5.143), the simulation results were in good agreement with the experimental
data. The pore-water pressure head changes obtained in the numerical simulations were similar to those observed in the laboratory experiments.

In the RLgs-95 column (Figure 5.144 and Figure 5.145), in general, the comparison shows that the pore-water pressure head profiles of the RL-95 and the gravelly sand as obtained from the numerical simulation moved slower than the pore-water pressure head profiles of the RL-95 and the gravelly sand as observed in the laboratory experiment. The experimental data also showed that the hydrostatic profile of the negative pore-water pressure head throughout the soil column was established around \( t = 4h \) (see Figure 5.145), after which there was no movement of the pore-water pressure head profile observed. In contrast to the experimental data, the simulation result showed that once water was completely drained in the soil column (around \( t = 10\text{min} \)) (see Figure 5.144), the pore-water pressure head profiles of the RL-95 and the gravelly sand moved more gradually and the hydrostatic profile of negative pore-water pressure was not established until \( t = 72h \) (see Figure 5.145).

The discrepancies of the numerical simulation result and the experimental data in the RLgs-95 column might be caused by two possibilities. First, the slower movement of the numerical simulation result as compared to the experimental data may be caused by the fact that in the numerical simulation, once water was completely drained, the pore-water pressure head of the gravelly sand reached the equilibrium conditions shortly and the permeability of the gravelly sand decreased significantly into an extremely low value. As the permeability of the gravelly sand was very low, while the RL-95 was still conductive enough for water infiltration, the pore-water pressure head profiles only moved gradually. The infiltrating water from the RL-95 then accumulated at the interface of the RL-95 and the gravelly sand, causing the pore-water pressure head in the interface of the fine-grained layer and the coarse grained layer to be slightly higher than the pore-water pressure head in the middle and lower parts of the gravelly sand (for example at \( t = 12h \); see Figure 5.145). Since the permeability of the gravelly sand became extremely low, it would take sufficiently long time for the hydrostatic profile of negative pore-water
pressure head to develop in the RLgs-95 column. Thus, it was not surprising that in the numerical simulation, the hydrostatic profile of negative pore-water pressure head did not develop until $t = 72h$ (see Figure 5.145).

The second possibility is that the hydraulic properties, particularly the residual matric suction, of the gravelly sand in the laboratory experiment changed after the upward infiltration test as a result of lime migration as discussed in Section 6.1.2 and Section 6.1.5. The addition of lime mainly in the upper part of the gravelly sand caused the residual matric suction head of the gravelly sand to increase by approximately to 5kPa. As the residual matric suction of the gravelly sand increased, the permeability of the gravelly sand in the range of 0kPa to 5kPa of matric suction was practically still high. This allowed water to be redistributed and the pore-water pressure head to decrease to -0.5m at the upper part of the gravelly sand (see Figure 5.145).

6.2.1.2. Volumetric water content profiles

Comparisons of the volumetric water contents obtained from the numerical simulations and the laboratory experiments are shown in Figure 5.146 to Figure 5.151.

For the capillary barrier models of the RGgs-50 and the RMgs-75 (Figure 5.146 to Figure 5.149), the numerical results agreed well with the experimental data. As exhibited by the experimental data, the sharp contrast between the volumetric water contents of the fine-grained layers (i.e., RG-50 and RM-75) and those of the coarse-grained layers (i.e., gravelly sand) was also shown in the numerical simulation results. The major discrepancy between the numerical simulation results and the experimental data was observed at the interface of the fine-grained layer and the coarse-grained layer, where the volumetric water contents measured during the laboratory experiments were much higher than the volumetric water contents obtained from the numerical simulations. This might be due to the fact that when the pore-water pressure head of the gravelly sand reached an equilibrium condition shortly after the water table was lowered, the unsaturated permeability of the
gravelly sand used in the numerical simulations was not as low as the unsaturated permeability of the gravelly sand developed in the laboratory experiments. During the drawdown test of water table in the laboratory experiments, the pore-water pressure head of the gravelly sand decreased rapidly and reached the equilibrium condition in a short time, causing the permeability of the gravelly sand to decrease to an extremely low value. As the decrease in the permeabilities of the fine-grained layers was more gradual, the fine-grained layers were still conductive for water infiltration. This allowed the infiltrating water to move down toward the underlying layer. As the permeability of the gravelly sand was extremely low, the infiltrating water was then accumulated at the interface of the fine-grained layer and coarse-grained layer. As time elapsed, more water accumulated at the interface between the fine-grained layer and coarse-grained layer, causing the relatively higher volumetric water content at the interface as compared to the volumetric water content in the gravelly sand. In contrast, as the unsaturated permeability of the gravelly sand used in the numerical simulations was relatively higher than that in the laboratory experiments once the pore-water pressure of the gravelly sand reached an equilibrium condition, the infiltrating water flowed downward into the gravelly sand and did not accumulate at the interface of the fine-grained layers (i.e., RG-50 and RM-75) and the coarse-grained layer (i.e., gravelly sand). As there was no water accumulation at the soil interface, the volumetric water content at the interface of the fine-grained layer and the coarse-grained layer was relatively low, as low as the volumetric water content of the gravelly sand. This suggests that the equation used to predict the permeability function of the gravelly sand could estimate well the unsaturated permeability of the gravelly sand for only to a certain extent until the pore-water pressure in the gravelly sand reached an equilibrium condition, after which the equation overestimated the unsaturated permeability of the gravelly sand.

Comparison of the numerical simulation result and the experimental data on the RLgs-95 column (Figure 5.150 and Figure 5.151) shows that there was a reasonable agreement in the volumetric water content of the RL-95 layer as obtained in the numerical simulation and those measured in the laboratory experiment. However, a
large discrepancy between the numerical simulation results and the experimental
data was found particularly in the gravelly sand. The volumetric water content of
the gravelly sand as measured in the laboratory experiments (i.e., around 0.45) was
much higher than the volumetric water content of the gravelly sand as obtained
from numerical simulations (i.e., around 0.05). Problems associated with lime
migration were suspected to be the main cause of the high volumetric water content
as measured by the TDR system (see also Section 6.1.2 and Section 6.1.5 for
discussions on lime migration).

6.2.2. Comparison of the results of rainfall tests

The pore-water pressure head profiles obtained during rainfall tests from the
numerical simulations and the laboratory experiments are compared and discussed
in Section 6.2.2.1. Subsequently, Section 6.2.2.2 presents discussions on the
comparison of the volumetric water content profiles obtained during rainfall tests
from the numerical simulations and the laboratory experiments.

6.2.2.1. Pore-water pressure head profiles

In general, comparisons of the pore-water pressure head profiles during rainfall tests
show that there were good agreement between results of the numerical simulations
and the experimental data. Results of the comparisons of the pore-water pressure
head profiles are partly shown in Figure 5.152 to Figure 5.163. The other results are
presented in Appendix D-1 to Appendix D-14.

In the RGgs-50 column and the RMgs-75 column, the pore-water pressure head
profiles obtained from the numerical simulations matched well with the pore-water
pressure head profiles measured in the laboratory experiments. For the RLgs-95
column, small discrepancies of pore-water pressure head profile were observed
between the results of numerical simulations and the laboratory experiments. This is
attributed to the fact that initial conditions of the rainfall tests in the numerical
simulations were not exactly the same as those in the laboratory experiments. As
previously mentioned in Section 6.2.1.1, the numerical model could not simulate
well the infiltration process during the drawdown test, where the hydrostatic profile
of negative pore-water pressure head developed well in the laboratory experiments.
whereas the numerical model showed that it took much longer time (i.e., more than 3 days) for the hydrostatic profile of negative pore-water pressure to develop throughout the soil column. It was suspected that the change in the hydraulic properties of the gravelly sand (i.e., the residual matric suction and the unsaturated permeability of the gravelly sand increased) due to lime migration caused the hydrostatic profile of pore-water pressure to develop throughout the gravelly sand in a short time. As the continuity of pore-water pressure to require that the pore-water pressure at the uppermost layer of the gravelly sand to be equal to the pore-water pressure at the lowermost layer of the RL-95, therefore, the hydrostatic profile of negative pore-water pressure was developed throughout the RL-95. In the numerical simulations, the permeability of the gravelly sand decreased to a low value once the pore-water pressure head in the gravelly sand reached approximately -0.1 m, after which the pore-water pressure head decreased gradually at a small rate toward a hydrostatic condition.

6.2.2.2. Volumetric water content profiles

Consistent with the pore-water pressure head profiles, the volumetric water content profiles of the RGgs-50 and the RMgs-75 obtained from the numerical simulations agreed well with the experimental data. Results of the comparisons are partly shown in Figure 5.164 to Figure 5.175, while the other results are presented in Appendix D-15 to Appendix D-28.

A small discrepancy was observed at the soil interface, where the laboratory experiments showed that the volumetric water content at the interface of the fine-grained layer and the coarse-grained layer was relative high, while the numerical simulation results showed that the volumetric water content at the soil interface was comparable to the volumetric water content of the gravelly sand (for example see Figure 5.164). It seems that the model could not simulate well the observation of the accumulated water at the interface of the fine-grained layer and the coarse-grained layer as observed in the laboratory experiments. As explained in Section 6.2.1.2, after a drawdown test of water table in the laboratory, the extremely low unsaturated permeability of the gravelly sand (once the pore-water pressure of the
gravelly sand reached an equilibrium condition) caused the infiltrating water from
the fine-grained layers (i.e., RG-50, RM-75, and RL-95) to accumulate at the
interface of the fine-grained layer and the coarse-grained layer (i.e., gravelly sand),
resulting in the relatively high volumetric water content at the soil interface. In
other cases, since the equation used to predict the permeability function of the
gravelly sand in the numerical simulations might overestimate the unsaturated
permeability of the gravelly sand after the pore-water pressure of the gravelly sand
reached an equilibrium condition, the infiltrating water from the fine-grained layer
was then allowed to infiltrate into the gravelly sand. As there was no water
accumulation at the soil interface, the volumetric water content at the soil interface
was equal to the volumetric water content of the gravelly sand.

6.3. Effects of Modification of the Residual Soil
As mentioned previously, the objective of this research is to improve the
performance of the residual soil as the fine-grained layer of a capillary barrier. The
improvement is mainly directed to the hydraulic properties (i.e., saturated
permeability, SWCC, and permeability function) and the shrinkage characteristics
by mixing the residual soil with coarse-grained contents (i.e., gravelly sand and
medium sand) and lime at different percentages. Effects of modification of the
residual soil are discussed in this section. Section 6.3.1 presents discussions on the
effects of modification on hydraulic properties. Meanwhile, effects of modification
on shrinkage characteristics are discussed in Section 6.3.2. Discussions on the
effects of modification on pore-water pressure are given in Section 6.3.3. Section
6.3.4 presents discussions on the effects of modification on the volumetric water
content, while the effects of modification on the drainage velocity are discussed
subsequently in Section 6.3.5.

6.3.1. Effects of modification on hydraulic properties
The effects of the soil mixing on the hydraulic properties of the residual soil are
discussed in this section.
6.3.1.1. Saturated permeability

Saturated permeability of the soils investigated in this study are shown in Table 5.1, 5.2, 5.3, and 5.4. In order to see clearly the effect of adding coarse-grained contents (i.e., gravelly sand and medium sand) and lime on the saturated permeability of the residual soil, the results of the permeability tests listed in Table 5.1, 5.2, 5.3, and 5.4 are plotted in a graph as shown in Figure 6.7. The coefficient of permeability at saturation, $k_s$, of the gravelly sand (i.e., $k_s = 7.6 \times 10^{-2}$ m/s) and the medium sand (i.e., $k_s = 3.28 \times 10^{-3}$ m/s) are about six orders of magnitude and five orders of magnitude, respectively, larger than the coefficient of permeability at saturation, $k_s$, of the residual soil (i.e., $k_s = 1 \times 10^{-7}$ m/s). The saturated permeabilities of the residual soil-gravelly sand mixtures and the residual soil-medium sand mixtures generally increase with the increase in coarse-grained contents. An interesting result of saturated permeability tests is exhibited in the mixture of residual soil-gravelly sand where the saturated permeability of the residual soil-gravelly sand mixtures remains relatively the same up to an addition of 50% gravelly sand. Large particles of the gravelly sand in the residual soil-gravelly sand mixtures might block the flow path of water. As a consequence, the saturated permeability of the residual soil-gravelly sand mixtures with an addition of gravelly sand up to 50% was as low as the saturated permeability of the residual soil alone. This result is similar to the findings observed by Shakoor and Cook (1990) for glacial till-gravel mixtures and by Shelley and Daniel (1993) for kaolinite-gravel mixtures (see Chapter 2).

For the addition of more than 50% gravelly sand, there was lack of fine-grained contents in the soil mixtures and the macro pores developed among the large particles of the gravelly sand were incompletely filled by the fine-grained contents of the residual soil. The saturated permeability of the residual soil-gravelly sand mixtures then started to increase. As more gravelly sand was added, the pore size of the residual soil-gravelly sand mixtures increased drastically to a size even larger than that of the residual soil-medium sand mixtures. This phenomenon may explain why the saturated permeability of the residual soil-gravelly sand mixtures becomes higher than that of the residual soil-medium sand mixtures, especially as observed in the RG-25 and RM-25.
As shown in Figure 6.7, the saturated permeability of the residual soil-lime mixtures tends to decrease with the increase in the lime content. Osinubi (1998) explained that the decrease in saturated permeability of the soil-lime mixtures may be caused by the formation of insoluble calcium silicates or aluminates or both, as a result of reaction between calcium ions of the lime and reactive silica or alumina, or both, in the soil. This formation obstructed water flow through the soil voids. In addition, the permeability tests, both the falling head method and the constant-head water flow method, were conducted right after the soil mixing. As a result, the additional flocculation due to cation exchange reaction, which might cause the increase in the saturated permeability, did not occur.

6.3.1.2. Soil-water characteristic curves

The drying soil-water characteristic curves of the soils used in this study were measured in the laboratory using Tempe cell and Pressure plate apparatuses. In order to have a continuous and wide range drying SWCC, the SWCC data were then fitted with the SWCC functions using the equation proposed by Fredlund and Xing (1994) with $C(\psi) = 1$ as suggested by Leong and Rahardjo (1997a).
Drying SWCCs of the soils used in this study are shown in Figures 5.6, 5.7, and 5.8. The measured data are presented using symbols, while the fitting curves are in the form of lines. Figures 5.6 and 5.7 show that the drying SWCCs of the residual soil-gravelly sand mixtures and the residual soil-medium sand mixtures are located in between the SWCCs of the residual soil and the coarse-grained contents. The slopes of the drying SWCC for the soil mixtures tend to increase with the increase in the coarse-grained contents. The slope of SWCC is a key parameter in this study as the coefficient of water volume change with respect to matric suction change is given by the slope of the SWCC (Leong and Rahardjo, 1997a). A steep slope, such as the slope of the SWCC of the gravelly sand, suggests that the water content of the soil will decrease significantly as the matric suction increases.

Parameters of the drying SWCCs for the soils used in this study are listed in Tables 5.5, 5.6, 5.7, and 5.8. The air-entry value $\psi_a$, the residual matric suction $\psi_r$, and the residual volumetric water content $\theta_r$ of the gravelly sand and the medium sand are much lower than those of the residual soil. The coarse-grained contents consisted of voids that were relatively larger than the voids in the residual soil. The macro pores of the coarse-grained soils desaturated faster than the micro pores of the residual soil, resulting in the low air-entry value $\psi_a$ and the low residual matric suction $\psi_r$ of the coarse-grained soils. In addition, the desaturation processes of the macro pores of the coarse-grained soils also caused only small amount of water to be left in the pores, resulting in the low residual volumetric water content $\theta_r$. Table 5.6 and 5.7 show that the air-entry value $\psi_a$, the residual matric suction $\psi_r$, and the residual volumetric water content $\theta_r$ of the residual soil-gravelly sand mixtures and the residual soil-medium sand mixtures tend to decrease with the increase in the gravelly sand and the medium sand contents, respectively. As the percentages of the coarse-grained contents were increased, more macro pores were developed in the soil mixtures and, therefore, the air-entry value $\psi_a$, the residual matric suction $\psi_r$, and the residual volumetric water content $\theta_r$ of the soil mixtures became smaller.

Different drying SWCC characteristics were obtained for mixtures with the addition of 3, 5, 7, and 9% lime to the residual soil. As shown in Figure 5.8 and Table 5.8,
the air-entry value \( \psi_a \) of the residual soil-lime mixtures increased as the lime content was increased. The increase in the air-entry value of the residual soil-lime mixtures is actually consistent with the decrease in the saturated permeability. The presence of lime causes the formation of insoluble calcium silicates or aluminates or both, resulting in the voids of the residual soil to become smaller. As a consequence, the soil mixture desaturated at a higher matric suction as compared to the residual soil.

6.3.1.3. Permeability functions

The permeability functions of the residual soil-gravelly sand mixtures, the residual soil-medium sand mixtures, and the residual soil-lime mixtures are shown in Figures 5.12, 5.13, and 5.14, respectively.

It is clearly shown that the shape of each permeability function is similar to the shape of the SWCC (see also Figures 5.6, 5.7, and 5.8). This is attributed to the fact that the equation for the permeability function prediction is essentially inferred from the SWCC function as described in Leong and Rahardjo (1997b). At a low matric suction (i.e., lower than 0.1 kPa), in general, the soils are still in their saturated conditions. The permeability of the soils starts to decrease at a matric suction corresponding to the air-entry value of the soils.

In the addition of coarse-grained contents to the residual soil, it is shown that the permeability functions of the soil mixtures are not located in between the permeability functions of the coarse-grained contents and the residual soil, although the SWCCs of the soil mixtures are located between the SWCCs of the coarse-grained contents and the residual soil. In addition, unlike the saturated permeability (Section 6.3.1.1), the permeability of the soil mixtures under unsaturated conditions changed insignificantly with the addition of coarse-grained contents, both the gravelly sand and the medium sand. This is reflected by the slopes of the permeability functions of the soil mixtures that are more or less the same with the slope of the permeability function of the residual soil, especially after 10kPa. It seems that the presence of the fine-grained contents derived from the residual soil in
the soil mixtures, even in a small quantity such as in the addition of 75% coarse-grained contents, has significant effects on the decrease in the soil permeability at higher matric suction values. The micro pores of the fine-grained contents of the soil mixtures retain the water content from decreasing rapidly.

6.3.2. Effects of modification on shrinkage characteristics

In this study, the volume change potential upon drying of the residual soil and the RG-75, RG-50, RM-75, RM-50 mixtures and the residual soil-lime mixture were investigated through shrinkage tests under ambient conditions. During the test, the changes in the soil water content and the soil volume were measured periodically.

Shrinkage behaviour of the soils investigated in this study is shown in Figure 5.17, 5.18, 5.19, and 5.20. As it was found to be difficult to maintain the saturation of the soil samples especially when the PVC tube was removed from the soil, the shrinkage tests were started from different initial degrees of saturation. During the drying processes, the void ratio $e$ of the soils decreased due to self-shrinkage until it reached a minimum value at which there was no further volume change observed.

![Figure 6.8 Volumetric shrinkage of the residual soil and the soil mixtures.](image)

Figure 6.8 shows the volumetric shrinkage experienced by the residual soil and the soil mixtures. In general, shrinkage potential of the residual soil decreased as the
coarse-grained contents were increased. The volume change due to shrinkage of the residual soil alone was about 18.7%. For the residual soil-gravelly sand mixtures with an addition of 25% gravelly sand (RG-75), the volumetric shrinkage was 15.3%. Meanwhile, the volumetric shrinkage of the RM-75 (i.e., the mixture with the addition of 25% medium sand) was 12.1%. As the percentage of the soil mixtures was based on the dry mass, the amount of the fine-grained contents of the residual soil in the RG-75 was relatively higher than that in the RM-75. In the RG-75, the coarse-grained particles of the gravelly sand floated in the matrix of the fine-grained contents of the residual soil. The poor contact among the coarse-grained particles caused the soil mixture to shrink highly.

The addition of 50% medium sand to the residual soil did not cause further reduction in the volumetric shrinkage of the residual soil-medium sand mixtures (i.e., RM-50), as the volumetric shrinkage of the RM-50 was comparable to the volumetric shrinkage of the RM-75. In contrast, the addition of 50% gravelly sand to the residual soil (i.e., RG-50) resulted in the volumetric shrinkage of the mixture to further decrease to 8.5%. In this case, although the fine-grained contents in the RG-50 were still high, the higher gravelly sand percentages caused the RG-50 to establish a better contact among the coarse-grained particles resulting in a more stable soil mixture with respect to the volumetric shrinkage.

For the residual soil-lime mixtures, the addition of 3% lime to the residual soil caused the RL-97 to shrink only 12.5% from its initial volume. The effect of the addition of 3% lime on the reduction of the volumetric shrinkage was actually comparable to the effect of the addition of 25% medium sand as shown in Figure 6.8. Further reduction of the volumetric shrinkage was observed in the soil mixture of 95% residual soil and 5% lime, where the volumetric shrinkage of the RL-95 was 7.8% from its initial volume. There were no further significant reductions of the volumetric shrinkage observed in the RL-93 and RL-91 as the soil mixtures only shrunk as much as 7.1% and 5.8%, respectively, from their initial volumes.
As mentioned in Chapter 2, the shrinkage characteristics shown by the residual soil-lime mixtures might be attributed to the two main processes commonly occurred in soil-lime reactions. The rapid physico-chemical reactions occurred in the RL-97 and the RL-95 within several hours after the soil mixing and involved the exchange of cations between clays present in the residual soil and calcium ions present in lime. The reaction then induced an agglomeration of the fine-grained contents into coarser-grained particles, forming a more stable soil mixture with respect to volumetric shrinkage.

The overall results imply that the volume change potential of the residual soil can be reduced by mixing the residual soil with certain percentages of coarse-grained contents or lime. The maximum reduction in the volumetric shrinkage was observed when 50% gravelly sand was added to the residual soil. As there were no further reductions of volumetric shrinkage after the addition of more than 25% medium sand or more than 5% lime to the residual soils, the RM-75 and the RL-95 can be considered as the “optimum medium sand content” for the residual soil-medium sand mixtures and the “optimum lime content” for the residual soil-lime mixtures, respectively.

6.3.3. Effects of modification on infiltration characteristics

Effects of addition of coarse-grained contents and lime on the infiltration characteristics of capillary barriers are compared and discussed in this section. Three soil mixtures, namely RG-50, RM-75, and RL-95 were used as the fine-grained layers of capillary barrier models. As explained in Section 4.2.2.2, the soil mixtures of RG-50, RM-75, and RL-95 were selected because there were considered to be the most optimum soil mixtures based on the hydraulic properties (particularly \( k_s \) value) and the shrinkage characteristics (see also Section 6.3.1 and Section 6.3.2).

6.3.3.1. Effects of modification on pore-water pressure

Effects of the addition of gravelly sand, medium sand, or lime to the residual soil on the pore-water pressure are discussed in this section. The discussions are initiated
by examining the changes in the pore-water pressure head during wetting process of rainfall test and followed subsequently by examining the changes in the pore-water pressure head during drying process of rainfall and drawdown tests.

6.3.3.1.1. Wetting process

Wetting process of infiltration was reflected in the first stage of a rainfall test, (i.e., during the application of rainfall). Profiles of pore-water pressure head of the RGgs-50 column during wetting process of rainfall tests are shown in Figures 5.25, 5.30, 5.35, and 5.40. Profiles of pore-water pressure head of the RMgs-75 column during wetting process of rainfall tests are presented in Figures 5.49, 5.54, 5.59, 5.64, and 5.69. Profiles of pore-water pressure head of the RLgs-95 column during wetting process of rainfall tests are shown in Figures 5.78, 5.83, 5.88, 5.93, 5.98, and 5.103.

In the wetting process, when the rainfall was applied to the top of the soil column, the pore-water pressure head at the upper part of the fine-grained layer started to increase from the ultimate negative pore-water pressure head toward positive values. This is reflected by the progressive movement of the pore-water pressure head profiles from the left to the right of the figure. As time elapsed, more water infiltrated into the soil column, resulting in further increase in the pore-water pressure head in the upper part of the fine-grained layer, which was accompanied by the increase in the pore-water pressure head in the lower part of the soil column.

The pore-water pressure head profiles show that the movement of the pore-water pressure head profiles in the RG-50 of the RGgs-50 column and the RM-75 of the RMgs-75 column were almost similar. However, the infiltration characteristics shown in those two fine-grained layers were different from the infiltration characteristics observed in the RL-95 of the RLgs-95 column. The pore-water pressure head profiles in the RG-50 and the RM-75 during rainfall application moved gradually from negative value to positive value (for example see Figure 5.25 and Figure 5.49). In contrast, the pore-water pressure head in the RL-95 increased rapidly from negative value toward positive value during a rainfall application (for example see Figure 5.93).
Figure 6.9 shows comparison of pore-water pressure head profiles in the RG-50, RM-75, and RL-95 during wetting process. A rainfall intensity of 3mm/h for 6h was applied to the top of the RGgs-50 column in the test of IC-RGgs-50R1 and to the top of the RMgs-75 column in the test of IC-RMgs-75R1 (see Table 4.1). Meanwhile, a rainfall intensity of 1.7mm/s for 6h was applied to the top of the RLgs-95 column in the test of IC-RLgs-95R4. Even though the rainfall intensity applied to the RLgs-95 column was slightly smaller than the rainfall intensities applied to the RGgs-50 column and the RMgs-75 column, during period t = 0 to t = 30min, the pore-water pressure head in the upper part of the RL-95 of the RLgs-95 column increased from -0.9m to -0.2m. During the same period, the pore-water pressure head in the upper part of the RG-50 of the RGgs-50 column increased from -0.5m to -0.4m, while the pore-water pressure head in the upper part of the RM-75 of the RMgs-75 column increased from -0.52m to -0.42m.
Similar characteristics were observed in other time steps and at other elevations in the fine-grained layers of the capillary barrier models, where the pore-water pressure head in the RL-95 of the RLgs-95 column increased larger than the pore-water pressure head in the RG-50 of the RGgs-50 column and in the RM-75 of the RMgs-75 column. Thus, it can be concluded that the rate of change in the pore-
water pressure of the RL-95 is much higher than the rate of changes in the pore-water pressures of the RG-50 and the RM-75 during wetting process.

The infiltration characteristics shown by the fine-grained layers during wetting process can be attributed to their hydraulic properties under unsaturated conditions. Figure 6.10(a) shows the wetting SWCCs of the fine-grained layers while the wetting permeability functions of these soils are shown in Figure 6.10(b). Figure 6.9 indicates that the infiltration process occurred in the RLgs-95 column was in the range of -1m to 0m of pore-water pressure head (or equal to 10kPa to 0kPa matric suction), while the infiltration processes occurred in the RGgs-50 and the RMgs-75 were in the range of -0.6m to 0m of pore-water pressure head (or equal to 6kPa to 0kPa matric suction). Figure 6.12(a) shows that the water-entry values (WEV) of the RG-50, RM-75, and RL-95 are 3.1kPa, 4.9kPa, and 28.6kPa, respectively (see also Table 5.9). It means that when the rainfall test was started in the IC-RLgs-95R4, the water-entry value of the RL-95 was higher than the maximum matric suction developed in the RL-95 (i.e., around 10 kPa) and the permeability function of the RL-95 was relatively high (i.e., around $10^{-7}$ m/s; see Figure 6.10(b)), causing water to enter the soil easily. The relatively steep slope of the wetting SWCC of the RL-95 indicates that the increase in volumetric water content and the increase in the permeability took place rapidly, causing the pore-water pressure head of the soil to increase in a short time as shown in Figure 6.9.

In contrast to the wetting process in the RL-95 of the RLgs-95 column, when the rainfall tests were started in the IC-RGgs-50R1 and in the IC-RMgs-75R1, the maximum matric suction developed in the RG-50 and the RM-75 (i.e., around 5.5kPa) were still higher than the water-entry values of the soils (i.e.,3.1kPa for the RG-50 and 4.9kPa for the RM-75) (see Figure 6.10(a)). As a result, more water was required to increase the pore-water pressures or to decrease the matric suction in the RG-50 and the RM-75 so that the water-entry values of the RG-50 and the RM-75 could be reached and water could start entering the soils. Figure 6.10(b) shows that the increase in the unsaturated permeabilities of the RG-50 and the RM-75 during wetting process (i.e., from 5.5kPa towards 0kPa) is more gradual than that of
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the RL-95. This explains the more gradual movement of pore-water pressure head profiles of the RG-50 and the RM-75 as compared to that of the RL-95.

In addition to the hydraulic property (i.e., the coefficient of permeability with respect to water phase, \( k_w \)), the difference in the rate of water infiltration in the fine-grained layers may also be attributed to the hydraulic gradient developed during rainfall application as the rate of water flow through a soil mass is influenced by the coefficient of permeability with respect to water phase, \( k_w \), and the hydraulic gradient (Eq. 3.10). For example, Table 6.1 presents the hydraulic gradients developed during rainfall tests as shown in Figure 6.9 (i.e., at \( t = 30 \)).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Total head 1, ( h_1 )</th>
<th>Total head 2, ( h_2 )</th>
<th>Hydraulic gradient, ( \Delta h / \Delta t )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( h_{p1} ) (m)</td>
<td>( h_{e1} ) (m)</td>
<td>( h_{p2} ) (m)</td>
</tr>
<tr>
<td>RG-50</td>
<td>-0.40</td>
<td>1</td>
<td>-0.050</td>
</tr>
<tr>
<td>RM-75</td>
<td>-0.40</td>
<td>1</td>
<td>-0.075</td>
</tr>
<tr>
<td>RL-95</td>
<td>-0.15</td>
<td>1</td>
<td>-0.475</td>
</tr>
</tbody>
</table>

It is clearly shown in Table 6.1 that the hydraulic gradient in the RL-95 was much higher that those in the RG-50 and the RM-75 under the same rainfall conditions. The relatively higher hydraulic gradient developed in the RL-95 than those developed in the RG-50 and the RM-75 caused the flow rate of water infiltration in the RL-95 to be higher than those in the RG-50 and the RM-75. As a result, the pore-water pressure head in the RL-95 increased faster than those in the RG-50 and the RM-75 (Figure 6.9).

For practical purposes of capillary barrier designs, therefore, the soil properties such as exhibited by the RG-50 and the RM-75, which have low water-entry values, are considered to be better since it will take longer for the fine-grained soils to be in saturated conditions and practically it will take even much longer time for the breakthrough to occur.
6.3.3.1.2. Drying process

Drying process of infiltration tests was shown during the drawdown of water table and in the second stage of a rainfall test (i.e., once the rainfall application was stopped). The pore-water pressure head profiles of the drawdown tests conducted on the RGgs-50, RMgs-75, and RLgs-95 are shown in Figures 5.22, 5.46, and 5.75, respectively. Figures 5.41, 5.70, and 5.84 show profiles of pore-water pressure head during drying processes of rainfall tests conducted in the IC-RGgs-50R4, IC-RMgs-75R5, and RLgs-95R2, respectively, with a comparable rainfall intensity and duration (i.e., 9mm/h for 2h; see Table 4.1). Other results of rainfall tests with a comparable rainfall intensity and duration are shown in Figure 5.36 (i.e., RGgs-50 column) and Figure 5.65 (i.e., RMgs-75 column).

Figure 6.11 demonstrates effect of modification of the residual soil on pore-water pressure during drying process. The pore-water pressure profiles presented in Figure 6.11 are summarized from the drying processes of rainfall tests conducted in

![Figure 6.11](image-url)
the IC-RGgs-50R1 (Figures 5.26), IC-RMgs-75R1 (Figure 5.50), and IC-RLgs-95R4 (Figure 5.94). During the wetting process, a comparable rainfall intensity and duration was applied to the top of the capillary barrier models, as previously mentioned in Section 6.3.3.1.1.

As shown in Figure 6.11, after the rainfall application was stopped (at \( t = 6h \)), the pore-water pressure head profiles in the RG-50 of the RGgs-50 column, the RM-75 of the RMgs-75 column, and the RL-95 of the RLgs-95 column moved to the left toward negative values. During period of \( t = 6h \) to \( t = 10h \), the pore-water pressure head in the upper part of the RG-50 of the RGgs-50 column decreased from \(-0.1m\) to \(-0.34m\), while the pore-water pressure head in the upper part of the RM-75 of the RMgs-75 column decreased from \(-0.2m\) to \(-0.42m\). Meanwhile, the pore-water pressure head in the upper part of the RL-95 of the RLgs-95 column decreased significantly from \(-0.1m\) to \(-0.85m\). This suggests that the rate of the decrease in the pore-water pressure heads of the RG-50 of the RGgs-50 column and the RM-75 of the RMgs-75 column was higher than the rate of the decrease in the pore-water pressure head of the RL-95 of the RLgs-95 column during drying process. Similar characteristics were observed at all elevations in the fine-grained layers. Furthermore, at \( t = 48h \), the pore-water pressure in the upper part of the RG-50 of the RGgs-50 column decreased to \(-0.5m\), while the pore-water pressure in the upper part of the RM-75 of the RMgs-75 column decreased to \(-0.48m\). The pore-water pressure head in the upper part of the RL-95 of the RLgs-95 column decreased to \(-0.95m\) at \( t = 48h \). The above data show that during period of \( t = 12h \) until \( t = 48h \), the pore-water pressure heads in the fine-grained layers (i.e., RG-50, RM-75, and RL-95) of the capillary barrier models were decreasing gradually. The infiltration characteristics of the fine-grained layers of the capillary barrier models during drying process can be explained by the drying SWCCs and the drying permeability functions of the soils.

Figure 6.12(a) shows the drying SWCCs of the RG-50, RM-75, and RL-95, while the drying permeability functions of the soils are shown in Figure 6.12(b). The air-entry values (AEV) of the RG-50, RM-75, and RL-95 are 0.2kPa, 0.6kPa, and
5.0kPa, respectively (see also Tables 5.6, 5.7, and 5.8). As the air-entry value of the RG-50 is the smallest, desaturation process occurred fastest in this soil. Meanwhile, the high air-entry value of the RL-95 suggests the soil desaturated gradually from the saturated condition.

As the volumetric water content of the soils decreased during the drying processes, the permeability of the soils also decreased. Figure 6.12(b) shows that at 3.4kPa (i.e., matric suction developed in the upper part of the RG-50 of the RGgs-50 column at $t = 12h$), the coefficient of permeability with respect to water phase, $k_w$, of the RG-50 decreased to about $6 \times 10^{-7}m/s$. At 4.2kPa (i.e., matric suction developed in the upper part of the RM-75 of the RMgs-75 column at $t = 12h$) the coefficient of permeability with respect to water phase, $k_w$, of the RM-75 of the RMgs-75 column also decreased to approximately $7 \times 10^{-7}m/s$, while at 8.5kPa (i.e., matric suction developed in the upper part of the RL-95 of the RLgs-95 column at $t = 12h$), the coefficient of permeability with respect to water phase, $k_w$, of the RL-95 of the RLgs-95 column decreased insignificantly to $8 \times 10^{-6}m/s$. As the permeability of the RL-95 was much higher than the permeabilities of the RG-50 and the RM-75, water flowed faster in the RL-95 than in the RG-50 and in the RM-75. These observations were found to be similar at all locations in the fine-grained layers.

As time elapsed, during period of $t = 12h$ until $t = 48h$, the unsaturated permeabilities of the RG-50 of the RGgs-50 column, the RM-75 of the RMgs-75 column, and the RL-95 of the RLgs-95 column were getting smaller, where the coefficients of permeability with respect to water phase, $k_w$, of the RG-50 of the RGgs-50 column and the RM-75 of the RMgs-75 column decreased to approximately $5 \times 10^{-7}m/s$ and the coefficient of permeability with respect to water phase, $k_w$, of the RL-95 of the RLgs-95 decreased to $4 \times 10^{-6}m/s$ (Figure 6.12b).

As the permeabilities of the soils became lower, water flowed slowly and the pore-water pressure head decreased gradually. These characteristics occurred not only in the upper part of the fine-grained layers but also at other elevations in the fine-grained layers.
In addition to the decrease in the unsaturated permeability, the hydraulic gradients in the soil columns also decreased significantly during drying processes of the rainfall tests. Tables 6.2, 6.3, and 6.4 show the hydraulic gradients in the RG-50, the RM-75, and the RL-95 developed during rainfall tests as shown in Figure 6.11.

Figure 6.12 (a) Drying SWCCs of the fine-grained layers of the capillary barrier models; (b) Permeability functions of the fine-grained layers of the capillary barrier models.
Table 6.2. Hydraulic gradients developed in the fine-grained layers at $t = 6h$.

<table>
<thead>
<tr>
<th>Soil</th>
<th>$h_{p1}$ (m)</th>
<th>$h_{e1}$ (m)</th>
<th>$h_{p2}$ (m)</th>
<th>$h_{e2}$ (m)</th>
<th>$\Delta h / \Delta l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG-50</td>
<td>-0.1</td>
<td>1</td>
<td>-0.025</td>
<td>0.5</td>
<td>0.85</td>
</tr>
<tr>
<td>RM-75</td>
<td>-0.2</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>0.60</td>
</tr>
<tr>
<td>RL-95</td>
<td>-0.1</td>
<td>1</td>
<td>-0.475</td>
<td>0.5</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Table 6.3. Hydraulic gradients developed in the fine-grained layers at $t = 12h$.

<table>
<thead>
<tr>
<th>Soil</th>
<th>$h_{p1}$ (m)</th>
<th>$h_{e1}$ (m)</th>
<th>$h_{p2}$ (m)</th>
<th>$h_{e2}$ (m)</th>
<th>$\Delta h / \Delta l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG-50</td>
<td>-0.35</td>
<td>1</td>
<td>-0.05</td>
<td>0.5</td>
<td>0.40</td>
</tr>
<tr>
<td>RM-75</td>
<td>-0.45</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>0.10</td>
</tr>
<tr>
<td>RL-95</td>
<td>-0.90</td>
<td>1</td>
<td>-0.5</td>
<td>0.5</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 6.4. Hydraulic gradients developed in the fine-grained layers at $t = 48h$.

<table>
<thead>
<tr>
<th>Soil</th>
<th>$h_{p1}$ (m)</th>
<th>$h_{e1}$ (m)</th>
<th>$h_{p2}$ (m)</th>
<th>$h_{e2}$ (m)</th>
<th>$\Delta h / \Delta l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG-50</td>
<td>-0.525</td>
<td>1</td>
<td>-0.05</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>RM-75</td>
<td>-0.05</td>
<td>1</td>
<td>-0.025</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>RL-95</td>
<td>-1</td>
<td>1</td>
<td>-0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

It is clearly shown in Tables 6.2, 6.3, and 6.4 that the hydraulic gradients in the fine-grained layers decreased with respect to time. At $t = 12h$, the hydraulic gradients in the RG-50, the RM-75, and the RL-95 had decreased significantly, causing water to infiltrate slowly and the pore-water pressure head to decrease gradually. At $t = 48h$, the hydraulic gradients of the RG-50 and RM-75 were practically very low (i.e., 0.5), while the hydraulic gradient of the RL-95 was zero, suggesting no water infiltration.

For capillary barrier designs, hydraulic properties of the RL-95 are preferred than that of the RG-50 and the RM-75 with respect to removal of water during drying process. A rapid water percolation is required during the drying process in order to allow the matric suction in the fine-grained layer of the capillary barrier to develop again and the fine-grained layer to be ready to receive subsequent rainfall loadings. In addition, rapid water removal is critical in maintaining the integrity of a capillary
barrier. Theoretically, if the matric suction of the fine-grained layer of the capillary barrier decreases to a value that is lower than the water-entry value of the coarse-grained layer, the breakthrough will occur.

6.3.3.2. Effects of modification on volumetric water content

Volumetric water content is an important parameter to determine water storage capacity of the fine-grained layer of a capillary barrier. A soil with high volumetric water content has a large storage capacity, as large amount of water can be stored. Figure 6.13 shows the profiles of volumetric water content at saturation of the capillary barrier models at the initial stage of drawdown tests of water table.

![Figure 6.13 Profiles of volumetric water content at saturation of the capillary barrier models.](image)

It is shown that the highest value of the volumetric water content at saturation as measured by the TDR system in the RL-95 of the RLg-95 column was 0.45 (see also Figure 6.4 for comparison with the oven-dried data). For the RGgs-50 column,
the volumetric water content at saturation of the RG-50 was 0.3. Meanwhile, the volumetric water content at saturation of the RM-75 of the RMgs-75 column was 0.35.

It is obvious that the RL-95 has the highest volumetric water content and, therefore, the highest water storage capacity. The high volumetric water content of the RL-95 may be related to the capability of the lime in absorbing water. Fine-grained soils generally have higher volumetric water content than coarse-grained soils. Since lime was essentially a fine-grained material, the addition of lime to the residual soil resulted in a high volumetric water content of the soil mixture.

6.3.3.3. Effects of modification on drainage velocity

In addition to the pore-water pressure and volumetric water content profiles, water infiltration processes in the capillary barrier models were also reflected by the drainage velocity. Drainage velocities measured during the tests of IC-RGgs-50R1, IC-RMgs-75R1, and IC-RLgs-95R4 are shown in Figure 6.14. The rainfall tests were conducted under a comparable rainfall intensity and duration (i.e., a rainfall intensity of 3mm/h for 6h) as mentioned previously in Section 6.3.3.1.1 and Section 6.3.3.1.2).

![Figure 6.14 Drainage velocities of the fine-grained layers of the capillary barrier models.](image-url)
Figure 6.14 shows that there was a delay in response of the digital weighing balance in measuring the drainage during rainfall tests. Water started to flow out from the RGgs-50 column during the rainfall test of IC-RGgs-50R1 and from the RMgs-75 column during the rainfall test of IC-RMgs-75R1 approximately at \( t = 5h \), after which the drainage velocity increased to a maximum value. In contrast, water started to flow out from the RLgs-95 column during the rainfall test of IC-RLgs-95R4 almost immediately after the rainfall was applied.

The results of drainage velocity measurements were actually consistent with the results of the pore-water pressure head measurements. In Section 6.3.3.1 mentioned that pore-water pressure head of the RL-95 of the RLgs-95 column increased rapidly once the rainfall test of IC-RLgs-95R4 was started. Apparently, breakthrough occurred immediately after the rainfall application and continued until rainfall application was stopped. Meanwhile, the pore-water pressure heads in the RG-50 of the RGgs-50 column and the RM-75 of the RMgs-75 column increased gradually as a result of gradual movement of wetting front in both capillary barrier models. As it took a longer time for water to infiltrate the RG-50 and the RM-75 as compared to the RL-95, there was a delay in response of the weighing balance in measuring the drainage from the RGgs-50 column and from the RMgs-75 column. It is the hydraulic properties (SWCCs and permeability functions) of the fine-grained layers that control the infiltration process in the capillary barrier models as discussed in Section 6.3.3.1.
Chapter 7
Conclusions & Recommendations

7.1. Conclusions

The following conclusions are drawn from this study.

1. Contrast in the permeability between the medium sand of Changi and the gravelly sand under an unsaturated condition was found to create a barrier effect for water infiltration in the field. This suggests that the capillary barrier system does not only work in the laboratory conditions, but also works in the field. In other words, the capillary barrier system works under different soil boundary conditions.

2. The hydraulic properties (saturated permeability, soil-water characteristics curve SWCC, and unsaturated permeability) and the shrinkage characteristics of the Bukit Timah residual soil can be modified by mixing the residual with gravelly sand, medium sand, or lime at different percentages.

3. The saturated permeabilities of the residual soil-gravelly sand mixtures and residual soil-medium sand mixtures were found to increase with the increase in the gravelly sand and medium sand percentages in the soil mixtures. In contrast, the saturated permeabilities of the residual soil-lime mixtures decreased with the increase in the lime percentage.
4. The air-entry values, $\psi_a$, of SWCCs of the residual soil-gravelly sand mixtures and the residual soil-medium sand mixtures decreased with the increase in the gravelly sand and medium sand percentages. Meanwhile, the air-entry values, $\psi_a$, of the SWCCs of the residual soil-lime mixtures increased with the increase in the lime percentage. In general, the permeability functions of the residual soil-gravelly sand mixtures, the residual soil-medium sand mixtures, and the residual soil-lime mixtures became steeper with the increase in the percentages of gravelly sand, medium sand, and lime, respectively. The permeabilities of the soil mixtures at high matric suctions were controlled by the remaining fine-grained soils so that the permeability functions of the soil mixtures were more or less parallel to the permeability function of the residual soil.

5. Results of the shrinkage tests showed that the volumetric shrinkage of the soil mixtures decreased with the increase in the percentages of the gravelly sand, medium sand, or lime.

6. The barrier effects of a capillary barrier were exhibited in the soil columns of RGgs-50, the RMgs-75, and the RLgs-95 during one-dimensional infiltration tests using a 190mm diameter, 1m high acrylic cylinder equipped with pore-water pressure, volumetric water content, and drainage measuring devices.

7. The hydrostatic profile of negative pore-water pressure was developed throughout the RLgs-95 column at the end of drying process in the laboratory experiments. However, the “static” nonequilibrium pore-water pressure developed in the gravelly sands of the RGgs-50 and the RMgs-75 columns caused the hydrostatic profiles of negative pore-water pressure not to develop in the soil columns of the RGgs-50 and the RMgs-75. The “static” pore-water pressure developed in the gravelly sands was also established in the numerical simulations.

8. The results of the infiltration tests showed that the low water-entry values, $\psi_w$, of the RG-50 (i.e., 3.1kPa) and the RM-75 (i.e., 4.9kPa) were found to be more
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effective than the high water-entry value, $\psi_w$, of the RL-95 (i.e., 28.6kPa) in maintaining negative pore-water pressure head during the wetting process. However, the high air-entry value, $\psi_a$, of the RL-95 (i.e., 5.0kPa) was found to be more effective than the low air-entry values, $\psi_a$, of the RG-50 (i.e., 0.2kPa) and the RM-75 (i.e., 0.6kPa) in draining out water during drying process. The drainage velocity measurements showed that breakthrough occurred faster in the capillary barrier model of RLgs-95 than in the capillary barrier models of the RGgs-50 and the RMgs-75.

9. The overall results of the infiltration tests conducted in the field and in the laboratory indicate that the tensiometer-bourdon gauge system and tensiometer-transducer system were quite effective and accurate in measuring the changes in the pore-water pressure in the soil layers. The Trase system along with the waveguides was also effective in measuring the volumetric water content of the soils up to certain accuracy. The electronic weighing balance allowed the drainage to be measured continuously during the infiltration tests.

10. The pore-water pressure head profiles obtained from the numerical simulations agreed well with the pore-water pressure head profiles measured in the laboratory experiments. As well, there was a good agreement between the volumetric water content profiles obtained from the numerical simulations and the volumetric water content profiles measured in the laboratory experiments. These suggest that the soil properties used in the numerical simulations were quite representative of soil conditions in the laboratory and field.

7.2. Recommendations

Further studies need to be performed in accordance with the performance of the fine-grained layer and coarse-grained layer of a capillary barrier. These studies involve:

- investigations of performance of the soils mixtures used in this study under a sloping capillary barrier system and different rainfall loadings.
• investigations of the effectiveness of the soil mixtures in releasing water under evaporative fluxes.

• investigations of other additive materials that can potentially be mixed with the residual soil in order to produce a more effective fine-grained layer of a capillary barrier.
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References


References


References


References


References


References


Appendix A

Investigation of barrier effect in the field
Appendix A

Appendix A-1 Information related to location of the field infiltration tests.

Appendix B

Investigation of hydraulic properties
Appendix B

Appendix B-1 Volume of water in the soil during drying SWCC of RG-25 (1 of 2).
Appendix B Volume of water in the soil during drying SWCC of RG-25 (2 of 2).
Appendix B

Appendix B-3 Volume of water in the soil during drying SWCC of RG-50 (1 of 2).
Appendix B-4 Volume of water in the soil during drying SWCC of RG-50 (2 of 2).
Appendix B

Appendix B-5 Volume of water in the soil during drying SWCC of RG-75 (1 of 2).
Appendix B

Appendix B-6 Volume of water in the soil during drying SWCC of RG-75 (2 of 2).
Appendix B

Appendix B-7 Volume of water in the soil during drying SWCC of RM-25 (1 of 2).
Appendix B

Appendix B-8 Volume of water in the soil during drying SWCC of RM-25 (2 of 2).
Appendix B-9 Volume of water in the soil during drying SWCC of RM-50 (1 of 2).
Appendix B-10 Volume of water in the soil during drying SWCC of RM-50 (2 of 2).
Appendix B-11 Volume of water in the soil during drying SWCC of RM-75 (1 of 2).
Appendix B-12 Volume of water in the soil during drying SWCC of RM-75 (2 of 2).
Appendix B

Appendix B-13 Volume of water in the soil during drying SWCC of RL-97 (1 of 2).
Appendix B-14 Volume of water in the soil during drying SWCC of RL-97 (2 of 2).
Appendix B

Appendix B-15 Volume of water in the soil during drying SWCC of RL-95 (1 of 2).
Appendix B-16 Volume of water in the soil during drying SWCC of RL-95 (2 of 2).
Appendix B-17 Volume of water in the soil during drying SWCC of RL-93 (1 of 2).
Appendix B-18 Volume of water in the soil during drying SWCC of RL-93 (2 of 2).
Appendix B-19 Volume of water in the soil during drying SWCC of RL-91 (1 of 2).
Appendix B

Appendix B-20 Volume of water in the soil during drying SWCC of RL-91 (2 of 2).
Appendix B

Appendix B-21 Tensiometers’ reading during wetting SWCC of RG-50.

Appendix B-22 Tensiometers’ reading during wetting SWCC of RM-75.
Appendix C

Laboratory infiltration tests
Appendix C

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Appendix C-1 Calibration of tensiometer-transducer system (Data Logger 1).
Appendix C

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**Appendix C-2** Calibration of tensiometer-transducer system (Data Loger 2).

**Appendix C-3** Verification of rainfall intensity before and after a rainfall test.
Appendix C-4 Verification of the uniformity of rainfall distribution during rainfall test of IC-RGgs-50R1.

Appendix C-5 Cumulative of drainage volume of the RGgs-50 column during the drawdown test of IC-RGgs-50Dr.
Appendix C-6 Cumulative of drainage volume of the RGgs-50 column during the rainfall test of IC-RGgs-50R1.

Appendix C-7 Cumulative of drainage volume of the RGgs-50 column during the rainfall test of IC-RGgs-50R2.
Appendix C-8 Cumulative of drainage volume of the RGgs-50 column during the rainfall test of IC-RGgs-50R3.

Appendix C-9 Cumulative of drainage volume of the RGgs-50 column during the rainfall test of IC-RGgs-50R4.
Appendix C

Appendix C-10 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75Dr.

Appendix C-11 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75R1.
Appendix C-12 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75R2.

Appendix C-13 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75R3.
Appendix C-14 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75R4.

Appendix C-15 Cumulative of drainage volume of the RMgs-75 column during the rainfall test of IC-RMgs-75R5.
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Appendix C-19 Cumulative of drainage volume of the RLgs-95 column during the rainfall test of IC-RLgs-95R3.
Appendix C

Appendix C-20 Cumulative of drainage volume of the RLgs-95 column during the rainfall test of IC-RLgs-95R4.

Appendix C-21 Cumulative of drainage volume of the RLgs-95 column during the rainfall test of IC-RLgs-95R5.
Appendix C

Appendix C-22 Cumulative of drainage volume of the RLgs-95 column during the rainfall test of IC-RLgs-95R6.
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Comparison of numerical simulation results and experimental data
Appendix D-1 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R3 and the NS-RGgs-50R3 (1 of 2).
Appendix D-2 Comparison of the pore-water pressure head profiles in the RGgs-50 column during rainfall test of the IC-RGgs-50R3 and the NS-RGgs-50R3 (2 of 2).
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Appendix D-6 Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R3 and the NS-RMgs-75R3 (2 of 2).
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Appendix D

Comparison of the pore-water pressure head profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R5 and the NS-RMgs-75R5 (2 of 2).

Appendix D-10
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Appendix D-12 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R3 and the NS-RLgs-95R3 (2 of 2).
Appendix D-13 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R4 and the NS-RLgs-95R4 (1 of 2).
Appendix D-14 Comparison of the pore-water pressure head profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R4 and the NS-RLgs-95R4 (2 of 2).
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Appendix D-15 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R3 and the NS-RGgs-50R3 (1 of 2).
Appendix D-16 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R3 and the NS-RGgs-50R3 (2 of 2).
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Appendix D-17 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IC-RGgs-50R4 and the NS-RGgs-50R4 (1 of 2).
Appendix D-18 Comparison of the volumetric water content profiles in the RGgs-50 column during rainfall tests of the IIC-RGgs-50R4 and the NS-RGgs-50R4 (2 of 2).
Appendix D

Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R3 and the NS-RMgs-75R3 (1 of 2).
Appendix D

Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R3 and the NS-RMgs-75R3 (2 of 2).
Appendix D-21 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R4 and the NS-RMgs-75R4 (1 of 2).
Appendix D-22 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R4 and the NS-RMgs-75R4 (2 of 2).
Appendix D-23 Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R5 and the NS-RMgs-75R5 (1 of 2).
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Comparison of the volumetric water content profiles in the RMgs-75 column during rainfall tests of the IC-RMgs-75R5 and the NS-RMgs-75R5 (2 of 2).
Appendix D-25 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R3 and the NS-RLgs-95R3 (1 of 2).
Appendix D-26 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R3 and the NS-RLgs-95R3 (2 of 2).
Appendix D-27 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R4 and the NS-RLgs-95R4 (1 of 2).
Appendix D-28 Comparison of the volumetric water content profiles in the RLgs-95 column during rainfall tests of the IC-RLgs-95R4 and the NS-RLgs-95R4 (2 of 2).