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<td>Author(s)</td>
<td>Rahardjo, Harianto; Santoso, Vera Amalia; Leong, Eng Choon; Ng, Yew Song; Hua, Chai Juay</td>
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NUMERICAL ANALYSES AND MONITORING PERFORMANCE OF RESIDUAL SOIL SLOPES

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ABSTRACT: Changes of pore-water pressures in unsaturated soil slopes due to rainwater infiltration is a crucial factor which affects the shear strength of soils and may trigger slope failures. Two residual soil slopes in two main geological formations in Singapore, the Bukit Timah Granite and the sedimentary Jurong Formation, were fully instrumented. Real-time monitoring systems were developed to examine pore-water pressure, rainfall and groundwater level in the slopes for over a year period. Characteristics of pore-water pressure distributions in both slopes during rainfall were highlighted and compared. The monitoring results indicate that the residual soil slope of Bukit Timah Granite has a thicker unsaturated zone due to a deeper groundwater table as compared to the residual soil slope of sedimentary Jurong Formation. A higher permeability of the residual soil of Bukit Timah Granite results in more rapid changes in negative pore-water pressure due to rainwater infiltration as compared to those of the residual soil of sedimentary Jurong Formation. Therefore, the residual soil slope of Bukit Timah Granite differs from the residual soil slope of sedimentary Jurong Formation in the characteristics of shear strength changes and factor of safety variation during rainfall. The differing characteristics of pore-water pressure responses during rainfall in these two residual soil slopes are analyzed based on the results of field measurements and numerical analyses.

KEYWORDS: pore-water pressure, matric suction, residual soil, slope instrumentation

1 INTRODUCTION

Rainfall-induced slope failure is a concern in many tropical areas. Global warming causes climatic changes which are affecting rainfall patterns in many parts of the world. Proper assessment and management strategies for the stability of residual soil slopes due to climatic changes and the reduction of the impact of
landslides on the environment can be carried out by characterizing the response of soil during rainwater infiltration.

Numerous research works have been conducted in geotechnical and geo-environmental engineering to study the importance of rainwater infiltration which is the most significant factor in triggering slope failures in tropical regions (Anderson, 1983; Brand, 1984, 1992; Ching et al., 1984; Tan et al., 1987; De Campos et al., 1988; Krahn et al. 1989; Anderson and Zhu, 1996; Anderson and Thallapally, 1996; Lim et al. 1996; Cheng, 1997; Au, 1998; Franks, 1999; Toll et al., 1999; Gasmo et al., 2000; Zhang et al., 2000; Tsaparas et al., 2003; and Rahardjo et al., 2005, 2006, 2007, 2010).

Soils in tropical areas generally consist of residual soils having negative pore-water pressure above the groundwater table. The change in pore-water pressure is a critical contributing factor to landslides in Singapore. Rainfall infiltration results in a decrease in the matric suction and subsequently reduces the soil shear strength. The reduction of shear strength may cause the slope to become unstable and prone to failure. The relationships of landslide occurrences with rainfall patterns have been studied in the past 40 years (Lumb, 1962, 1975; Brand, 1984; Finlay et al., 1997 and Dai and Lee, 2001).

Significant progress has been made in laboratory and field measurements of suction (Ridley and Burland, 1993, 1995; Ridley and Wray, 1996; Delage, 2004; Melani et al., 2002, 2005; and Yang et al., 2006), physical modelling (Alonso et al., 1990; Vaunat et al., 2000; Gapollipoli et al., 2003 and Schnellmann et al., 2010), parametric study (Tsaparas et al., 2002 and Rahardjo et al., 2007) and numerical modelling (Olivella et al., 1996; Gatmiri and Delage, 1997; Gatmiri et al., 1997; Alonso et al., 1998; Gasmo et al., 1999; Lee et al., 2009 and Rahardjo et al., 2001, 2010) associated with quantifying the effects of rainfall on slope stability. Studies on the effects of rainfall on residual soil slopes using pore-water pressure measuring devices had been carried out by Sweeney (1982), Pitts (1985), Fredlund and Rahardjo (1993), Öberg (1995), Lim et al. (1996), Ridley et al. (1998), Gasmo et al. (1999), Rezaur et al. (2003) and Tsaparas et al. (2003), Li et al. (2005), Cui et al. (2008), Mendes et al. (2008), Rahardjo et al. (2008) and Tarantino et al. (2008).

Despite the existence of abundant field and laboratory data, there are still many uncertainties in accurately estimating the soil moisture, matric suction and groundwater level in relation to rainfall infiltration. There is still great need for quality
field data to clarify these uncertainties and it will be valuable to utilize measurements from a fully instrumented slope to clarify some of the important issues in slope performance.

This study attempts to present continuous field measurements of rainfall, infiltration and pore-water pressure; to evaluate the magnitude, time-dependent behavior and contours of these variables and to provide explanations for the variations in pore-water pressure response in relation to rainfall events. This information can then be incorporated into slope stability analyses that account for changes in shear strength of soil due to infiltration. The results are expected to have relevance to other geographical locations under similar climatic conditions and to contribute to the limited literature available on hydrologic responses of slopes in the tropical regions.

To investigate mechanism of rainfall-induced slope failure, two instrumented residual soil slopes were studied. The monitoring results of the pore-water pressure responses were analyzed to give a quantitative understanding of the change in factor of safety of the slope due to rainwater infiltration. Some other monitoring results and their interpretations from both sites were also presented in Rahardjo et al. (2009). In this paper, numerical analyses were conducted to simulate the field condition. Given the rainfall input data, the pore-water pressure distribution was obtained by performing a transient seepage analysis using the finite element program SEEP/W (Geo-Slope International Ltd., 2004a). The computed pore-water pressure distribution was subsequently used to calculate the factor of safety of the slope by the means of limit equilibrium method of slices using the computer program SLOPE/W (Geo-Slope International Ltd., 2004b).

## 2 FIELD STUDY

The geology of Singapore (Figure 1) can be classified into three main formations: (a) the sedimentary Jurong Formation in the west, (b) igneous rocks of Bukit Timah Granite in the northwest and centre and (c) semi-hardened alluvium or Old Alluvium in the east, as described in PWD (1976), Pitts (1984) and Leong et al. (2002). Two-thirds of Singapore contains residual soils of granitic and sedimentary rocks. The two instrumented slopes studied in this paper consist of residual soils from the sedimentary Jurong Formation and the Bukit Timah Granite.
3 FIELD INSTRUMENTATIONS

Real-time monitoring systems in the slopes were used to study the response of soil slope to environmental changes. The measuring devices installed in the slope consist of jet-fill tensiometers, tipping-bucket rain gauges and piezometers to measure negative pore-water pressure, rainfall and groundwater level, respectively.

At each site, sixteen tensiometers, three piezometers and one rain gauge were installed in four rows as illustrated in the schematic diagram of relative position and arrangement of field instrumentation for Jalan Kukoh and Marsiling Road sites in Figure 1. Each row consisted of four tensiometers installed at depths of 0.64, 1.31, 1.66 and 2.08 m below the ground surface.

The Casagrande piezometers with depth transmitters being connected to the data acquisition system were used to monitor the groundwater table changes in response to rainfall. Three piezometers at Jalan Kukoh with the piezometer depth of 13, 10 and 16 m were installed at the crest, middle and toe of the slope, respectively. Three piezometers at Marsiling Road with the piezometer depth of 20, 14 and 11 m were installed at the crest, middle and toe of the slope, respectively.

Data from these instruments were captured by the data acquisition system and subsequently transmitted to a secured website using General Packet Radio Service (GPRS). Data acquisition systems were set up for the full-scale field experiment. Instrumentation huts were constructed at the crest of the slopes to house the data loggers and power supplies. The data acquisition systems consisted of sensors, cables, data loggers and power supplies. Pressure transducers were used in all the tensiometers and piezometers for automated data collection. The data loggers were configured to collect data at 10 minutes intervals if there was rainfall and at 30 minutes intervals if there was no rainfall. Real-time information can be processed and accessed through the secured website.

4 RESIDUAL SOIL SLOPES OF SEDIMENTARY JURONG FORMATION AND BUKIT TIMAH GRANITE

4.1 Site Description

The Jalan Kukoh site is located on a natural slope covered with grass at a height of 11.74 m and an inclination of 33°. This site is underlain by residual soils of the sedimentary Jurong Formation. Borehole logs obtained from the Jalan Kukoh site indicate that subsoils generally consist of clayey sands. Fill material observed from
the borehole data contains firm sandy silt, soft clay with sand and rock fragments, loose silty sand with rock and woods and some foreign materials.

The Marsiling Road site is a natural slope located at the northwest region of Singapore. The slope is approximately 17 m high with an average inclination of about 26.7°. This site consists of residual soils from the Bukit Timah Granite, mainly silty sand and sandy silt. The soil geometries and properties of the soils at the Jalan Kukoh and Marsiling Road slopes are shown in Figures 2 and 3, respectively.

4.2 Soil Properties

The basic soil properties of residual soils at Jalan Kukoh and Marsiling Road slopes are presented in Table 1. Soil-water characteristic curves (SWCC) for the soils were fitted using Fredlund and Xing SWCC equations (1994) as presented in Figure 4. In general, SWCC for the residual soil from the Bukit Timah Granite at Marsiling Road has a higher saturated volumetric water content, a lower air-entry value, a steeper slope and a higher residual water content than those of SWCC for the residual soil from the sedimentary Jurong Formation at Jalan Kukoh. Permeability functions for the residual soils were estimated using the statistical method and presented in Figure 5. The SWCC parameters and saturated permeability obtained from laboratory tests, $k_s$, of these materials are summarized in Table 2.

Shear strength parameters of the clayey sand, silty sand and sandy silt layers were required for the slope stability analyses. The shear strength parameters for an unsaturated soil such as effective cohesion $c'$, effective angle of internal friction $\phi'$ and $\phi^b$ angle were determined from consolidated drained triaxial tests as presented in Table 1. In the numerical analysis, the low retaining wall at the toe of Jalan Kukoh slope was assumed to have a unit weight, $\gamma = 24$ kN/m$^3$ and a low permeability ($k_s = 10^{-11}$ m/s). The retaining wall was assumed as a soil layer with an effective cohesion, $c' = 5$ kPa and an effective internal friction angle, $\phi' = 40$°.

4.3 Initial Condition and Boundary Conditions

The finite element mesh used and the boundary conditions for the seepage analysis are presented in Figures 2 and 3 for Jalan Kukoh and Marsiling Road slopes, respectively. The left and right edges were located at a distance of $3H_s$ ($H_s$ = slope height) from the crest and the toe, respectively, in order to avoid any influence of the
boundary conditions on the seepage process within the slope area. Transient seepage analysis was performed by applying a small uniform infiltration to the slope surface for a long duration to represent the net flux of water on the site in order to obtain the initial profile of pore-water pressure. Different amounts of rainfall with different rainfall durations were applied to the slope for different soil types. For instance, a rainfall intensity of $1 \times 10^{-7}$ m/s was applied to Jalan Kukoh slope for 23 days and a rainfall intensity of $1 \times 10^{-7}$ m/s was applied to Marsiling Road slope for 62 days.

Subsequently, another transient seepage analysis was carried out for the actual rainfall. Flux boundary condition was applied on the seepage face along the slope surface by considering the potential seepage face review. The flux boundary condition was assigned to the ground surface which allowed infiltration to enter at a rate depending on soil permeability and hydraulic gradient and the remaining amount of rainwater will runoff. In addition, no ponding condition was applied to the seepage analyses. It means that the software will check that every node at the ground surface has zero or negative hydraulic head.

The side boundaries below the groundwater table were specified as constant total head boundaries and the side boundaries above the groundwater table were specified as no flow zone or nodal flux, $Q$, equal to zero. The total head applied corresponded to the hydrostatic condition. Tensiometer measurements in Singapore have been found to have a limit value of 75 kPa negative pore-water pressure (Rahardjo, 2000). Therefore, a hydrostatic pore-water pressure distribution with a limiting negative pore-water pressure of 75 kPa was set as an initial condition for the slope model in this paper.

Seepage analyses of the Jalan Kukoh slope were performed using SEEP/W and the actual rainfall patterns on 26 September 2008 with a total rainfall of 155.2 mm for 5 h as depicted in Figure 6. On the other hand, seepage analyses of the Marsiling Road slope was carried out using the actual rainfall pattern of 11 March 2008 with a total rainfall of 74.4 mm for 6 h as illustrated in Figure 7.

4.4 Seepage Analyses

Total head contours were generated using Surfer (Golden Software, Inc. 1997), based on the field measurements of negative pore-water pressure in the Jalan Kukoh residual soil slope of the sedimentary Jurong Formation before and at the end
of rainfall as presented in Figure 8. Total head is equal to the sum of the elevation head, $h_e$, and the pore-water pressure head, $h_p$. Water flow occurs as result of the difference in total head. Comparison of total head contours obtained from the numerical analyses and total head contours based on the field measurements of the Jalan Kukoh residual soil slope before and at the end of rainfall are shown in Figure 9. Total head contours obtained from the field measurements in the Marsiling Road residual soil slope from the Bukit Timah Granite before and at the end of rainfall were generated using Surfer as presented in Figure 10. Comparison of total head contours obtained from the numerical analyses and total head contours based on the field measurements in the residual soil slope from the Bukit Timah Granite before and at the end of rainfall are shown in Figure 11.

Generally, it can be seen that the total head contours obtained from the field measurement and the numerical analysis of the residual soil slope from sedimentary Jurong Formation before and at the end of rainfall were in reasonably good agreement. The presence of significant matric suctions near the ground surface during the dry period contributed to the stability of the slope. It appears that water flow occurred within the slope during the dry period when water moved upward due to evaporation and also across the slope as shown in Figures 8(a) and 9(a). Matric suctions near the ground surface decreased during rainfall due to water infiltration into the slope as illustrated in the total head distributions in Figures 8(b) and 9(b). The total head contours in Figure 8(b) indicates that water infiltrated into the slope and flowed from the crest to the toe of the slope.

The total head contours obtained from the field measurement and numerical analyses of the residual soil slope from Bukit Timah Granite before and at the end of rainfall were in a good agreement. Figures 10(a) and 11(a) indicate the existence of a hydraulic head gradient between the slope crest and toe even during the dry period. In other words, there was a movement of water from the crest to the toe of slope in addition to the upward movement of water due to evaporation. As a result, the lower slope area remained wetter than the upper slope area. Figures 10(b) and 11(b) show that the hydraulic gradient during the wet period caused a downward movement of rainwater into the slope and across the slope, increasing the pore-water pressure and reducing matric suction during wet period. The contour lines in Figures 11(a) and 11(b) representing total heads of 134 m and 135 m indicate more drainage downslope
due to the hydraulic head gradient during the wet period and rising of the groundwater table at the toe of the slope.

Comparison of pore-water pressure profiles obtained from the numerical analyses and field measurements near the crest, middle and the toe of the residual soil slope from sedimentary Jurong Formation are presented in Figure 12. It can be seen from Figures 12(a) and 12(b) that the numerical analyses could simulate the process in the field with reasonably good agreement. Pore-water pressure profiles obtained from the numerical analyses near the crest and middle of the slope were very close to the data measured in the field. Negative pore-water pressures approached zero near the ground surface due to rainfall. It was suspected that cavitation occurred in the tensiometers at Row A (at the crest of the slope) and therefore there was no proper measurement of negative pore-water pressure available at the crest.

Results of the numerical analyses did not quite agree with the data measured near the toe of the slope (Figure 12(c)). In the numerical analyses, the initial pore-water pressure profile near the toe of the slope did not match with the field data that had positive pore-water pressures about 18 kPa at depths of 1.66 and 2.08 m from the ground surface. The actual pore-water pressures near the toe of the slope (below elevation 104.4 m) built up faster than the computed pore-water pressures from the numerical analysis, causing the discrepancies below this elevation. The discrepancies were caused by the ponding of water near the toe of the slope at the beginning of the rainfall and thus the pore-water pressure did not change significantly when the actual rainfall occurred.

Comparison of pore-water pressure profiles obtained from the numerical analyses and field measurements near the crest, middle and the toe of the residual soil slope from Bukit Timah Granite are presented in Figure 13. It can be seen that generally the numerical analyses could simulate the process in the field with reasonably good agreement. Pore-water pressure profiles obtained from the numerical analyses near the crest and middle of the slope were very close to the field measurements. The measured negative pore-water pressure in the residual soil slope of Bukit Timah Granite increased to zero values after rainfall. At the toe of the slope, positive pore-water pressures up to 12 kPa were measured after rainfall.

Figures 13(a) and 13(b) appear to have drastic changes in pore-water pressure distribution at a depth of 141m due to a contrast in the unsaturated coefficient of permeability between the silty sand (\(k_{sat} = 6 \times 10^{-6} \) m/s) and sandy silty sand (\(k_{sat} = \)
3.3 \times 10^{-5} \text{ m/s}) layers that limits downward water movement. Since there is only a silty sand (the 1st layer) above the groundwater table at Row D, such a drastic change is not observed in Figure 13(d).

The infiltration rates at the slope face, top and toe due to rainfall on 26 September 2008 at Jalan Kukoh slope as obtained from the numerical analyses are also shown in Figure 6. The infiltration rates at the slope face, top and toe (i.e. about 20 mm/h) were much lower than the rainfall rate with a maximum rate of 148 mm/h. Figure 14 shows the rate of increase in pore-water pressure and rainfall rate against time as obtained from the field measurement. As soon as the rainwater infiltrated, an immediate increase in pore-water pressure took place with a maximum rate of increase of 24 kPa/h at an elapsed time of 0.5 hour at 0.64 m depth from the ground surface. At this depth, the rate of increase in pore-water pressure gradually slowed down to 3.4 kPa/h and eventually reached zero beyond elapsed time of 2.83 hours. Meanwhile, a less significant rate of increase in pore-water pressure due to rainfall was shown at the deeper depths of tensiometer, e.g., 1.31, 1.66 and 2.08 m depths from the ground surface.

Figure 15 shows the percentage of increase in pore-water pressure and the accumulated rainfall against time as obtained from the field measurement of Jalan Kukoh slope. It can be seen that the response of pore-water pressure increase due to rainfall was fastest at the depth of 0.64 m below the ground surface as demonstrated by the steepest gradient of increment during the first half hour and its trend resembled that of the accumulated rainfall. This could be attributed to the fact that water flowed down faster near the slope surface which consisted of 1.5 m depth of fill material of heterogeneous and coarser particle sizes. The tensiometers located at depths 1.31, 1.66 and 2.08 m below the ground level showed a slower response in the reduction of negative pore-water pressure due to the rainfall events because the rainwater required a longer time to reach these deeper depths. The rates of increase in pore-water pressure at depths of 1.66 and 2.08 m were faster than that at 1.31 m depth could be due to the presence of lateral flow from the upper slope to the lower slope within the 1st clayey sand layer below the fill material of 1.5 m thick.

The infiltration rates at the slope face, top and toe due to the rainfall on 11 March 2008 at Marsiling Road slope as obtained from the numerical analyses are also shown in Figure 7. The infiltration rate at the top of the slope appeared to be highest, followed by those at the slope face and at the slope toe. The variation in infiltration
rate of the residual soil slope from the Bukit Timah Granite at Marsiling Road appeared to resemble the variation in the rainfall rate closely (Figure 7) due to the high permeability of the top layer of the slope (i.e., the sandy silt layer). This is in contrast with the variation in infiltration rate of the residual soil slope from the sedimentary Jurong Formation at Jalan Kukoh that did not resemble the variation in the rainfall rate (Figure 6) due to the low permeability of the top layer of the slope.

Figure 7 shows that as the soil became wet, the permeability increased and for a rainfall rate (i.e. \(1.33 \times 10^{-5} \text{ m/s}\) in the early stage of rainfall) greater than \(k_{\text{sat}} = 6 \times 10^{-6} \text{ m/s}\) (surface soil), the initial infiltration rate (45.69 mm/h = \(9.20 \times 10^{-4} \text{ m/s}\)) was higher than the \(k_{\text{sat}}\) value by as much as 1.8 times. In other words, rainwater could infiltrate the soil at a rate higher than the saturated permeability of the soil. This was made possible due to the high hydraulic head gradient, \(i\) available for the flow, resulting in a high infiltration rate, \(\nu\), even greater than \(k_{\text{sat}}\) following Darcy’s law, \(\nu = k_{\text{sat}} \cdot i\). This observation agrees with the results reported by Gasmo et al. (2000). It should be noted that a rapid infiltration rate may result in a rapid decrease in the shear strength of the soil and consequently the stability of the slope.

Figure 16 presents the rate of increase in pore-water pressure and rainfall rate against time as obtained from the field measurement in Marsiling Road slope. It can be seen that the maximum rate of increase in pore-water pressure at the depth of 0.64 m from the ground surface (i.e. 13.8 kPa/h) occurred after the third peak of the rainfall event at the elapsed time of 2.3 hours. Meanwhile, the maximum rate of increase in pore-water pressure was 9.24 kPa/h at the depth of 1.31 m below the ground surface, which occurred after the fourth peak of the rainfall event at the elapsed time of 4.67 hours. At the depth of 1.66 m below the ground surface, the rate of increase in pore-water pressure reached its maximum rate of 3.18 kPa/h during the fifth peak of the rainfall event at the elapsed time of 5.5 hours. At the deeper depth of 2.08 m below the ground surface, only small changes in pore-water pressure were observed as it was not quite affected by the rainfall event. From Figure 16, it can be observed that the increase in pore-water pressure throughout the depth due to the rainwater percolation in response to a rainfall event has a time lag of about 0.3 to 0.6 hours in this case.

Figure 16 indicates that as soon as the rain begins, there are rapid responses of the increase in pore-water pressure due to infiltration at the depths of 0.64 and 2.08 m below the slope surface. However, while the rainwater infiltration continues with time, the response of increase in pore-water pressure at the depths of 1.66 and 1.31 m
below the ground surface is faster than the response at the depths of 0.64 and 2.08 m below the ground surface because of a lateral water flow from the upper slope towards the lower slope.

In Figure 17, the percentage of increase in pore-water pressure and the accumulated rainfall are plotted against time using data from the field measurement at Marsiling Road slope. A rapid response of the increase in pore-water pressure due to rainfall is shown at the depths of 0.64 and 2.08 m below the ground surface with the steepest gradient occurred after the second peak of rainfall event (i.e. elapsed time of 2 to 3 hours). The tensiometers located at the depths of 1.31 and 1.66 m below the ground surface showed a slower response in reduction of negative pore-water pressure due to rainfall. After the elapsed time 2.5 hours, the response of increase in pore-water pressure at the depth of 2.08 m is faster than the response at the depth of 1.66 and 1.31 m below the ground surface. The presence of high water content of soil as a result of water accumulation at the toe of the slope was suspected to be the cause for the faster rate of increase in pore-water pressure at the depth of 2.08 m.

4.5 Slope Stability Analyses

Rainwater infiltrated into the unsaturated zone of the soil and increased the negative pore-water pressure. When the rainwater percolated downward, the matric suction at deeper depths also decreased, causing a reduction in shear strength and subsequently the factor of safety of the slope. As the infiltrating rainwater became lesser than the rainwater percolating downward into the slope, pore-water pressures above the wetting front started to decrease again, shear strength of the soil increased and consequently the factor of safety of the slope started to increase.

The computer program SLOPE/W (Geo-slope International Ltd., 2004b) was used to perform the limit equilibrium slope stability analysis. Bishop’s simplified method was selected in the analysis due to its capability in calculating factor of safety with accuracy close to the more rigorous methods (Ching and Fredlund, 1984; Fredlund and Krahn, 1977). The slope stability analyses were performed by importing the obtained pore-water pressure distributions from the seepage analyses. The time dependent pore-water pressure distributions were used to calculate the factor of safety with time.

Figure 18 presents the factor of safety with time from the slope stability analyses using SLOPE/W. The initial factor of safety of the Jalan Kukoh residual soil
slope was 1.37 which decreased gradually to a value of 1.33 when the rainfall stopped (i.e. elapsed time of 5 hours) and continued to decline to a minimum value of 1.28 at 25 hours after the rainfall stopped (i.e. elapsed time of 30 hours). The minimum factor of safety for the Jalan Kukoh slope did not coincide with the time when the rainfall stopped, but at 25 hours after the rainfall stopped. The lower permeability of the residual soil slope from the sedimentary Jurong Formation resulted in a slower rainwater infiltration which delayed the occurrence of the minimum factor of safety to sometime later after the rainfall had stopped.

A steeper gradient of factor of safety reduction in Marsiling Road slope during rainfall illustrates the important role of permeability of the soil. The high permeability of the soil allowed rainwater to infiltrate and percolate downward quickly to deeper depths. As a result, a rapid increase in the pore-water pressure would develop in the slope. As a consequence, the factor of safety of the Marsiling Road slope decreased rapidly until it reached a minimum value of 1.57 when the rainfall stopped, i.e. at elapsed time of 6 hours.

The deeper initial water table location in Marsiling Road slope might contribute to the higher initial factor of safety of the slope as compared to that of Jalan Kukoh slope. On the other hand, the factor of safety variation during rainfall is controlled by the applied rainfall characteristics (including rainfall pattern, intensity and duration) and the soil properties of the slope, particularly the coefficient of permeability.

Figure 18 also shows that the recovery rate of factor of safety of the Marsiling Road slope after rainfall was faster than that of the Jalan Kukoh slope due to the higher permeability of the residual soil from the Bukit Timah Granite. Figures 19 and 20 present the critical failure surfaces of Jalan Kukoh and Marsiling Road slopes, respectively. The depths of the critical failure surfaces of Jalan Kukoh slope before rainfall and at the elapsed time of 30h, when the minimum factor of safety occurred, were 4.6 m and 3.1 m from the slope surface, respectively. Meanwhile, the depths of the critical failure surfaces of Marsiling Road slope before and at the end of rainfall were 9.1 m and 5.3 m from the slope surface, respectively.

5 CONCLUSIONS
Two residual soil slopes from Bukit Timah Granite and sedimentary Jurong Formation have been fully instrumented with real-time monitoring systems to provide
valuable information of changes in pore-water pressure, rainfall and groundwater level during rainfall and dry periods. These changes were simulated in numerical analyses in order to quantify the response characteristics of two different residual soil slopes to rainfall. The following conclusions can be drawn from the monitoring results and numerical analyses:

1. The residual soil slope of the sedimentary Jurong Formation has a shallower initial groundwater table, resulting in a lower initial factor of safety than the residual soil slope of the Bukit Timah Granite.

2. The variation of factor of safety during rainfall is determined by the applied rainfall to the slope (rainfall pattern, intensity and rainfall duration) and the properties of the soil (coefficient of permeability and shear strength) in the slope.

3. The variation in infiltration rate of the Marsiling Road residual soil slope in the Bukit Timah Granite appeared to resemble closely the variation in the rainfall rate because of the high permeability of top layer of the slope. Meanwhile, the variation in infiltration rate of the Jalan Kukoh residual soil slope in the sedimentary Jurong Formation did not resemble the variation in the rainfall rate due to the low permeability of the top layer of the slope.

4. A faster rate of increase in negative pore-water pressure due to rainwater infiltration was observed in the residual soil slope of the Bukit Timah Granite as compared to that in the residual soil slope of the sedimentary Jurong Formation. This was caused by the higher permeability of the residual soil of the Bukit Timah granite as compared to the permeability of the residual soil of the sedimentary Jurong Formation. Consequently, the factor of safety of the residual soil slope of the Bukit Timah Granite decreased at a faster rate during rainfall and also increased at a faster rate after rainfall stopped as compared with the factor of safety of the residual soil slope of the sedimentary Jurong Formation.

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REFERENCES


## List of Tables

### Table 1 Basic properties of soils

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<th>sedimentary Jurong Formation (JF)</th>
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<tr>
<td>Plasticity index, $PI$</td>
<td>32.73</td>
<td>13.41</td>
</tr>
<tr>
<td>Gravel (%)</td>
<td>3.93</td>
<td>0</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>73.07</td>
<td>73.45</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>11.67</td>
<td>13.5</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>15.67</td>
<td>13</td>
</tr>
<tr>
<td>Fines (%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>USCS group symbol</td>
<td>SC</td>
<td>SC</td>
</tr>
</tbody>
</table>

USCS: Unified Soil Classification System

### Table 2 Fredlund and Xing parameters for residual soils

<table>
<thead>
<tr>
<th>Description</th>
<th>sedimentary Jurong Formation (JF)</th>
<th>Bukit Timah Granite (BT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clayey sand I</td>
<td>Clayey sand II</td>
</tr>
<tr>
<td>Saturated coefficient of permeability, $k_s$ (m/s)</td>
<td>8.21x10^{-6}</td>
<td>8.21x10^{-6}</td>
</tr>
<tr>
<td>Saturated volumetric water content, $\theta_s$</td>
<td>0.4020</td>
<td>0.5800</td>
</tr>
<tr>
<td>Fitting parameter a (kPa)</td>
<td>298</td>
<td>65</td>
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<tr>
<td>Fitting parameter n</td>
<td>0.62</td>
<td>1.27</td>
</tr>
<tr>
<td>Fitting parameter m</td>
<td>1.08</td>
<td>1.54</td>
</tr>
<tr>
<td>Air-entry value (AEV)</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Residual volumetric water content, $\theta_r$</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Residual suction, $\psi_r$ (kPa)</td>
<td>7000</td>
<td>600</td>
</tr>
</tbody>
</table>

$C(\psi) = 1$ as suggested by Leong and Rahardjo (1997)
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