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Sensing and Monitoring for Assessment of Rainfall-induced Slope Failures in Residual Soil

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ABSTRACT:

Real-time monitoring can be used for assessment of the effect of climatic conditions on slope stability. However, the cost of real-time monitoring system can be costly. Therefore, there is a need to have a methodology to select critical slopes for monitoring of stability of these slopes using a comprehensive field instrumentation throughout the year. In this study, the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) model is used to generate slope susceptibility map in Singapore. This method was selected since it could incorporate the unsaturated soil properties in the spatial analyses of water infiltration and factor of safety calculation. Only limited studies were conducted in the past for the establishment of slope susceptibility map by incorporating unsaturated soil mechanics principles. In addition, most of the studies focused on mountainous areas. This paper presents relatively new research works on the development of slope susceptibility map for a densely populated area like Singapore. The study area was limited to the residual soil from Bukit Timah Granite in Singapore. TRIGRS system helps to determine zones which are highly susceptible to failure. Hence, the instrumentation can be used to monitor the high risk area during dry and rainy periods. A selected slope A was instrumented with tensiometers, moisture sensors, piezometers and rain gauge. All instruments were connected to a data logger for real-time monitoring. The

changes of pore-water pressures and soil moistures with time during wet and dry periods were used for slope stability analyses. Factor of safety variations with time could be used for assessment of slope stability especially during heavy rainfall.

Keywords: Landslides; Finite-element modelling; Seepage

1. INTRODUCTION

Climate changes may cause extreme weather events in the world, such as the alteration in the rainfall pattern, amount, intensity and frequency. Previous studies indicated that rainfall events have become more intense in a number of countries (Strauch et al., 2015). The increase in rainfall intensity may aggravate the impact of natural hazards, namely flooding and slope failures. Prolonged and heavy rainfalls in tropical countries have been observed in recent years. The report from IPCC (IPCC, 2013) indicated that it is expected rainfall intensity in Southeast Asia, including Singapore will increase about 2 to 15 %, according to A1B scenario of the forth assessment report (AR4). The increase in rainfall intensity could present significant challenges to the management of water resources and drainage, biodiversity and greenery, natural slope, network infrastructure and building infrastructure. Changes in rainfall patterns, in particular, will influence the flux boundary conditions across ground surface. The changes in groundwater level could reduce the suction and the shear strength of the soil that may result in rainfall-induced slope failures (Fredlund et al., 2012).

Rainfall-induced slope failures are commonly observed in residual soils of Singapore during rainy seasons (Rahardjo et al., 2013). In view of the effects of climate change, greater amounts of rainfall are expected in the future and thus there is a need to prevent future rainfall-induced slope failures. A slope susceptibility map is one common method

that can be used to identify areas that are susceptible to slope failures. Therefore, many studies have been carried out to develop a susceptibility map for a region, particularly in the tropics which is associated with high intensity of rainfall.

Past experience of slope failures in the world encouraged researchers to develop methods to monitor slope conditions in real-time (Greco et al., 2013; Alonso et al., 2013; Gofar and Lee, 2008; Leung and Ng, 2016 and Rahardjo et al., 2014). The use of relevant field instruments (i.e. piezometers, tensiometers) are necessary for the assessment of changes in pore-water pressures, water content and stability of slope in real time. Then, the warning system can be established to prevent slope failure as well as to ensure the effectiveness of the preventive measures especially during heavy rainfall. Numerical analyses should be used to verify the results from field instrumentation.

In this study, the slope susceptibility map was developed for slopes within the residual soil from Bukit Timah Granite. A slope located at a high risk area was instrumented with tensiometers, piezometers and rain gauge to monitor the factor of safety variations during dry and rainy periods.

2. LITERATURE REVIEW

Rainfall-induced slope failure is one of the potential natural hazards in Singapore's urban terrain. Most of the instabilities occurred in residual soils and were caused by long and heavy rainfall events (Greco et al., 2010; Leung et al., 2011; Regmi et al., 2014; Rahardjo et al., 2014). The rainwater infiltration results in the variations of pore-water pressure and water content with depth. Hence, the water content increases and the matric suction decreases. As a result, the soil shear strength decreases and it may trigger slope failure (Olivares and Picarelli, 2003; Alonso et al., 2003; Ng et al., 2001; Rahardjo et al., 2010).

The risk of rainfall-induced slope failure occurring in Singapore is increased by climate change. Studies by Kristo et al. (2017) indicated that Singapore has experienced an increase in annual rainfall over the past 30 years due to the effect of climate change. Studies by Strauch et al. (2015) have shown an upward trend in both the intensity and frequency of heavy rainfall events. Therefore, it is important to identify and improve the high risk slopes to prevent slope failures during rainfall event.

Digital soil mapping has become a common tool that is used in the study of soil science owing to the advancement of technology. Compared to the traditional soil survey methods, digital soil mapping is relatively less tedious, less costly and faster to generate the distribution of soil properties (Grunwald, 2010). Slope susceptibility mapping has become a common research topic as it could help researchers, engineers or town planners to predict the possibility of slope failure and come up with mitigation measures against potential slope failures (Shahabi and Hasim, 2015; Erenner et al., 2016; Basharat et al., 2016).

Understanding the unsaturated soil behaviour is essential in designing numerous engineering works, such as soil excavation, residual soil slopes analyses and soil compaction (Fredlund et al., 2012). Unsaturated soil mechanics is particularly of importance in analysing rainfall-induced slope failures. In Singapore, slope failures during rainfalls are commonly associated with residual soil slopes that are often found with a significant depth of unsaturated zone above the groundwater table. The unsaturated zone is defined by the presence of the negative pore-water pressures above the ground water table (Fredlund and Rahardjo, 1993). In this case, it is very important to incorporate the spatial distribution of unsaturated soil properties in the development of slope susceptibility map.

Study by Bennett and Doyle (1997) indicated that the cost for slope repair is more expensive than the cost associated with slope preventive measures. Therefore, it is

necessary to understand the flux boundary condition and hydrological behaviour of a residual soil slope in order to protect it from failure. Several studies have been conducted through field instrumentation and numerical analyses to explore the influence of climate changes (snow and rainfall), flux boundary conditions (evaporation, infiltration) and groundwater changes on stability of soil slope (Kilsby et al., 2009; Springman et al., 2003; Cascini et al., 2006). Some researchers also incorporated the monitoring results from piezometers, tensiometers and rain gauge into transient seepage analyses and limit equilibrium analyses for investigating the stability of slope during rainy periods. The seepage and stability analysis results indicated that slope failures are commonly observed during heavy rainfalls in Italy (Greco et al., 2013), Spain (Alonso et al., 2013), Malaysia (Gofar and Lee, 2008), Hongkong (Leung and Ng, 2016) and Singapore (Rahardjo et al., 2014). Past analyses by Rahardjo et al. (2012) demonstrated that the location of the critical slip surface and the slope failure event could be estimated with the incorporation of rainfall intensity, pattern and soil properties in the seepage and slope stability analyses. As a result, suitable preventive measures can be provided for different soil slopes in minimizing the casualties and damages due to slope failures.

Ayalew and Yamagishi (2005) utilized GIS analysis to generate a landslide susceptibility map of the Kakuda-Yahiko Mountains of Central Japan. Eighty-seven landslides that occurred in the area and seven geological and topographical parameters - lithology, bed rock-slope relationship, lineaments, elevation, slope gradient, aspect and proximity to roads – were used in the development of landslide susceptibility map. Ercanoglu and Gokceoglu (2001) used GIS analyses to generate a landslide susceptibility map of Yenice in Turkey. They used historical data from 57 identified landslides in the investigated area. Six parameters, slope angle, slope aspect, land use, weathering depth, water conditions and topographical elevation were incorporated in their analyses. Baeza

and Corominas (2001) used multivariate statistics techniques to develop a landslide susceptibility map of the Spanish Eastern Pyrenees. They incorporated the following factors: slope angle, mean watershed, land use, watershed area and cross-section of slope in the development of landslide susceptibility map. Glade et. al. (2012) generated landslide susceptibility models focussing on rock fall as well as soil and debris slides in Lower Austria. In the model, they included previous landslide/rock slide data, geology, land cover, topographic indicators (e.g. slope angle, height, aspect, slope position), rainfall distribution and terrain models. It can be seen that majority of past works focused on the development of slope susceptibility map without incorporating soil properties in their models.

The latest work by Kim et al. (2014) utilized YS-Slope model for the evaluation of the areas that are susceptible to landslides in Mount Umyeonsan, South Korea. They incorporated saturated and unsaturated soil properties data together with the terrain model, geology, rainfall distribution and historical landslide in their model. However, their work focused on the mountainous area, not an urban area like Singapore.

In this paper, the development of slope susceptibility map for a densely populated area within a residual soil of Singapore is presented. The works included the use of saturated and unsaturated soil properties together with other required parameters in the GIS analyses to obtain the distribution of factor of safety for the slopes in the residual soils of Bukit Timah Granite in Singapore.

3. DEVELOPMENT OF SLOPE SUSCEPTIBILITY MAP

Slope susceptibility maps are powerful tools for enhancing slope stability preparedness to withstand climate changes. Study by Bathurst et al. (2010) indicated that the reliable slope susceptibility maps should be developed based on the incorporation of the appropriate modeling methods, datasets and validation techniques. Previous studies were only limited

to the development of slope susceptibility map with the incorporation of index properties and saturated engineering properties of soil. No study has been carried out to utilize unsaturated soil properties in the development of slope susceptibility map. In this study, the unsaturated soil properties were used to assess the stability of the residual soil slopes in Singapore.

Geostatistical analyses provide methods for processing data in digital soil mapping. The core elements of geostatistical analyses are the interpolation methods. One commonly used method is Kriging which is an interpolation method based on the distance-weighting and semivariogram function approach to find the unknown data between measured/known locations. Li and Heap (2011) observed that Ordinary Kriging is the most popular Kriging method. It is the simplest form of Kriging (e.g., no trend, no stratification etc.) since it requires only a single variable (univariate method). However, this type of Kriging is also the most robust among all types of Kriging. In this study, Ordinary Kriging was used in the development of geospatial distribution of the saturated and unsaturated properties of the residual soil from Bukit Timah Granite. The geostatistical analyses were carried out using ArcGIS software (McCoy and Johnston, 2002). In this study, a coordinate reference system was used in the establishment of the georeferenced map.

The Kriging analyses require basic map of Singapore and the soil properties data from 16 site investigation locations in the residual soil from Bukit Timah Granite. The data included variables of SWCC (i.e. air-entry value, AEV), saturated permeability (k_s) and shear strength parameters (i.e. c' , ϕ' and the angle indicating the increase in shear strength due to the increase in matric suction, ϕ^b angle). Based on Kriging analyses, the study area was divided into seven zones. The zones were divided based on similarity of hydraulic and shear strength properties of each zone. The relevant soil properties for each zone are presented in Table 1. The required soil properties in the analysis using TRIGRS are:

saturated permeability (k_s), hydraulic diffusivity, effective cohesion (c'), effective frictional angle (ϕ'), and unsaturated shear strength angle (ϕ^b) (Table 1). The soils in this region are characterized by a relatively higher coefficient of permeability and a lower air-entry value in comparison to those of the residual soil from Jurong formation in the western part of Singapore. Figure 1 presents the location of site investigation and zones used for the development of slope susceptibility map.

In this study, the slope susceptibility map was developed by conducting 1-D based seepage analysis and infinite slope based stability analysis using Transient Rainfall Infiltration and Grid-based Regional Slope Stability (TRIGRS) code. The TRIGRS implemented the unsaturated soil mechanics principles for analyses of the unsaturated zone above the groundwater table. For the unsaturated zone, the code solves the 1-D Richard's equation expressing the rate of change of volumetric water content within a soil depth due to water flow through unsaturated zone. The water table rise is observed with the accumulation of the infiltrated water at the base of unsaturated soil (Baum et al., 2008). The volumetric water content and hydraulic conductivity relationship with matric suction for the unsaturated zone is modelled using Gardner's equation. On the other hand, an analytical solution to a pressure diffusion equation based on Iverson (2000) is used to model the pore-water pressure increase at the basal boundary between saturated and unsaturated zone.

The depth used to calculate factor of safety in the analysis was assumed to be 6.5 m since typical critical slip surface for residual soil slopes in Singapore is located at a depth less than 6.5 m. Based on the Code of Practice of Power and Utilities Board, Singapore (PUB, 2013) for drainage system design, the maximum total amount of rainfall in a day is 533.2 mm. Therefore, a rainfall loading of 22 mm/h for 24 hours (or total rainfall of 528 mm per day) was used in the analysis. Transient pore-water pressure, which is a function

of rainfall intensity, was introduced with the assumption that shallow slip surfaces are tension-saturated. The Iverson (2000) model requires only three parameters to predict the magnitude and timing of the transient pore water pressure, that are rainfall intensity, duration, and soil hydraulic diffusivity. Some limitations of this approach are the soil was assumed homogeneous for one particular zone, the direction of water was assumed isotropic in the analysis, the rainwater infiltration was calculated based on 1-D infiltration model and the stability analysis was carried out based on an infinite slope model. However, these assumptions produced the worst scenario of the factor of safety variations. Hence, the slope susceptibility map could generate more conservative slope safety.

In addition to soil parameters, TRIGRS also requires the spatial distribution of slope angle (Figure 2) and elevation (Figure 3) as input for stability analyses of the residual soil slopes from Bukit Timah Granite. These two layers were extracted from Digital Elevation Model (DEM) of Singapore. The 1-D infiltration analyses to obtain changes in groundwater table and the subsequent identifications of the critical depth with respect to the lowest factor of safety were carried out at each 1-m pixel of the elevation and slope angle layers. The variations in factor of safety at all pixels were imported into ArcGIS 10.5 to obtain a spatial distribution of factor of safety within the residual soil slopes from Bukit Timah Granite.

Figure 4 presents the slope susceptibility map generated using 1-D infiltration and slope stability analysis incorporating saturated and unsaturated soil properties. The slope susceptibility map illustrates the variations of factor of safety between the range of 0.5 and 10. The minimum allowable factor of safety for slopes in Singapore is 1.5 (HDB, 2012; LTA, 2010). The susceptibility classes, high, medium, low, and very low for the map are associated with the following range of factor of safety (FOS) : <1.5, 1.5~3, 3~6, and >6, respectively. In Figure 4, the green, yellow and orange coloured regions have factor of safety greater than 1.5. Therefore, they can be classified as zones with slopes having lower

risk of failure. In contrast, the pixels with red colour having factor of safety equal or less than 1.5, indicating the critical slopes which are prone to failure and require preventive measure or slope monitoring.

Singapore is a small country with a high number of population. Typical slope heights in Singapore are around 5 to 10 m. The slopes are located in between residential houses and public buildings. The pixels indicating factor of safety equal or less than 1.5 are related to slopes with high risk since the failures of these slopes may endanger the surrounding houses or buildings. In this case, the slope susceptibility map will benefit Singapore in managing the slopes within the urban area of Singapore especially those critical slopes with a factor of safety lower than 1.5.

4. SLOPE INSTRUMENTATION

Rainfall-induced slope failures are commonly observed within residual soil slope with significant changes in pore-water pressures and soil moisture contents. Therefore, piezometers, tensiometers and soil moisture sensors are necessary to monitor the changes of negative pore-water pressure and moisture contents in the unsaturated zone as well as the rising of ground water level inside the slope. The long term real-time monitoring is required since rainfall occurred throughout the whole year in Singapore. In addition to the above-mentioned instrumentation, rain gauge is also required to monitor the rainfall intensity. The combination of these three instruments' readings provides important information about the relationship between rainfall intensity and changes of pore-water pressures and moisture contents within the slope. The on-line monitoring system provides real time monitoring instrumentation data. The internet connection enables the data to be accessed from any personal computer everywhere. The on-line monitoring system can be used to set the warning system in order to take precaution action prior to the occurrence of

slope failure. Figure 5 shows the schematic diagram of instrumentation for an on-line monitoring system.

This study focused on the real-time monitoring of Slope A (Figure 4) located at the high risk area within the residual soil from Bukit Timah Granite. The rain-gauge at Slope A was placed on an open area at 1.0 m above the ground at the toe of the slope to determine the rainfall intensity. The location was high enough to prevent water splashing into the rain gauge, but not too high since it might be affected by the wind. A tipping bucket rainfall gauge, was utilized to collect the rainfall data. The rain gauge was calibrated to tip for every 0.25 mm of rainfall. Regular maintenance of the rainfall gauge was conducted twice a week as dust and insects may enter the tipping bucket and affect the accuracy of measurement.

The schematic diagram and layout of monitoring instruments at Slope A are shown in Figure 6. Two piezometers were installed at the crest (P1) and at the toe (P2) of the slope to monitor the response of groundwater table during dry and rainy periods. P1 was located at a depth of 7 m from the slope surface at the crest and P2 was located at a depth of 4 m from the slope surface at the toe. Casagrande type piezometers were used in this study for their reliability (Barnes, 2016). This type of piezometer was used to measure the pore-water pressure by installing the piezometer tip in between two bentonite layers at the designated depth of installation. The zone above the bentonite layers was sealed with a grout to avoid migration of water into the intake area of the piezometer. The pressure transducers were inserted into the Casagrande piezometer hole to allow for automated data acquisition. The diameter of the Casagrande piezometer (50 mm) was larger than diameter of the transducer (25 mm) in order to insert it into the standpipe. The pressure transducer recorded a reading by converting pore-water pressure to a frequency signal through a diaphragm, a tensioned steel wire, and an electromagnetic coil. It allowed for accurate monitoring of groundwater level changes in response to rainfall.

Soil moisture sensors and tensiometers were installed vertically into the soil layers. Two pairs of jet-fill tensiometers and soil moisture sensors were located near the crest of the slope (TM1 and SM1; TM2 and SM2), whereas the other two pairs were placed at the sloping face (TM3 and SM3; TM4, SM4) (Figure 6). The pressure transducers were connected to tensiometers for measurement of pore-water pressure from -100 to 100 kPa with 0.1 kPa resolution. Prior to installation of tensiometers, the saturation conditions of the ceramic tips should be maintained properly (Figure 7a). The tensiometer is filled with distilled and de-aired water mixed with sulphate solution to minimize the development of fungus and algae inside the tensiometer (Figure 7b) during a long period of measurement. The holes for tensiometer installation were cored using a hollow pipe with 24 mm diameter (Figure 7c). The variations of soil moisture content within soil layers in this study were monitored using soil moisture sensors with response time of 0.5 s and accuracy of 1 %. Details of installation and calibration of tensiometers and soil moisture sensors can be seen in Rahardjo et al. (2014).

Battery and solar panel were used to supply power for data logger. The corrugated tubes were utilized to protect cables from damages due to rainfall and insects. The recording of the instrumentation data was set at a 10-minute interval during rainfall events. It continued reading at a 10-minute interval after rain stopped for 6 hours before it switched into 3 hours interval of reading during dry periods (Figure 5). General packet radio system (GPRS) in a modem was used to send all data from the data logger to a computer server for on-line monitoring system. All raw data were stored in the server to be processed automatically based on the requirement of the project. The server launched the raw and processed data in a dedicated website.

5. MONITORING RESULTS

The rainfall records for the period between 1 July 2016 and 30 June 2017 are shown in Figure 8. It was observed that a 2819 mm cumulative annual rainfall occurred within this period. This amount of rainfall was higher than the average yearly rainfall in Singapore (2328.7 mm) for the period between 1869 and 2016 (MSS, 2016). It was also observed that the number of days with rainfall was 178 days which was equal to the average yearly number of rainy days in Singapore. The climatic conditions in Singapore are within two monsoon seasons (the Northeast Monsoon and the Southwest Monsoon). The Northeast Monsoon occurs between December and early March where the wet period occurs from December to January and the dry period occurs between late January and early March. The Southwest Monsoon occurs between June and September with short periods of showers/thunderstorms in the afternoon. The monitoring data from the rain gauge showed that the rainfall trends at Slope A were quite different from the typical trends in Singapore. The average rainfall in Singapore for the month of December was higher than 300 mm. However, the cumulative rainfall at Slope A in December 2016 was 214.3 mm. The average monthly rainfall for the month of May in Singapore was lower than 200 mm. However, the total rainfall in May 2017 at Slope A was 331 mm.

Figure 8 also demonstrated that the cumulative rainfalls in September, October and November 2016 at Slope A were higher than the average rainfall for the months of September, October and November in Singapore. Periods between March and May are usually drier as compared to the inter-monsoon periods in Singapore. In January 2017, the recorded maximum daily rainfall was 103.8 mm. A dry period was observed within the first two weeks in January 2017. However, the very wet period was observed at the end of the month. The wettest month was encountered in November 2016 (311.3 mm) with 21 rainy days during the monitoring period. The driest month was observed in August 2016 (98.6

mm). The maximum total rainfall was recorded in May 2017 (331 mm) with only 14 rainy days.

The variations in groundwater table recorded by piezometer 1 (P1) and piezometer 2 (P2) are presented in Figure 9. P1 and P2 recorded initial groundwater table of 6.1 m and 2.4 m from the surface of the crest and the toe of slope, respectively. The monitoring of piezometers indicated the maximum groundwater table of 4.4 m and 0.4 m below the soil surface at the crest and at the toe of the slope, respectively. On the other hand, the minimum groundwater table position was 7.2 m and 3.3 m below the soil surface at the crest and at the toe of the slope, respectively. Figure 9 was plotted with the incorporation of the difference between the elevation at the crest and at the toe of the slope. Hence, it can be seen that the groundwater table within the soil layer was almost flat with an average fluctuation of 2.8 m.

The responses of tensiometers during dry and rainy periods at Slope A are presented in Figure 10 in terms of the average daily basis. The tensiometers were placed at horizontal distances of 0.4 m (TM4), 2.4 m (TM3), 3.8 m (TM2), and 4.6 m (TM1) from slope face at a depth of 2 m (Figure 6). The responses of TM4 at a distance of 0.4 m were very significant due to the long dry period in December 2016 and early January 2017. With the exception of this period, the pore-water pressure in all tensiometers varied from -5 to -25 kPa throughout the monitoring period. The soil moisture responses to the rainfall infiltration in the slope A are shown in Figure 11. It shows that the sensor responses corresponded closely to the climatic conditions during dry and rainy periods. The volumetric water content within the residual soil layer varied from less than 10% to 55% between 1 July 2016 and 30 June 2017. Soil moisture sensors recorded a significant change in volumetric water content at depths of 2.4 m and 3.8 m after the heavy rainfall that occurred on 10 November 2016 following a 5-day dry period.

The monitoring data from the website can be used as an input in seepage and slope stability analyses. Based on the pore-water pressure distribution, water content profiles and the factor of safety from the numerical analyses, alert and alarm levels can be set up. The alert and alarm levels are based on values of pore-water pressure, water content and rainfall intensity from tensiometer, piezometer and rain gauge readings. The alert level signals the engineers to go to the site and check the condition of the slope. The result of the observation can be used to determine whether preventive measures should be performed to protect the slope from impending failure. The alarm level signals the staff to take action to mitigate the slope stability problem.

6. SEEPAGE AND SLOPE STABILITY ANALYSES

Numerical analysis was conducted to study the effect of rainfall on the stability of residual soil Slope A. The numerical model of Slope A is presented in Figure 12. The finite element program, Seep/W (Geoslope International Pte Ltd, 2012a) was used to perform seepage analyses. The spatial function was used to establish the initial pore-water pressure conditions of the slope model based on the recorded pore-water pressures from tensiometer readings at Slope A. Spatial function is a function in Seep/W to assist the users in setting up the initial condition of the model accurately. The distance between the slope and the side of the slope model was set to three times the height of the slope to avoid the influence of the side boundary conditions. The finite element model down to 5 m below the slope surface had a mesh size of approximately 0.5 m, smaller than elements in other parts of the slope, in order to obtain accurate results within the infiltration zone.

The boundary conditions applied to the finite element model are illustrated in Figure 12. A constant total head, h_w , on each side was applied as the boundary condition along the sides of the slope model below and above the groundwater table. Rainfall was applied to

the slope surface as a flux boundary, q . Ponding was not allowed to occur on the slope surface. This meant that when a flux greater than the permeability of the soil was applied to the top boundary, the seepage model would not allow pore-water pressures greater than 0 kPa to build up at the ground surface. This simulated the actual field conditions where the excess rainfall at the slope surface was removed as runoff.

The two-dimensional seepage problem can be solved using the governing differential equation as illustrated in Equation (1) as follows:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t} \quad (1)$$

where:

H = the total head;

k_x/k_y = coefficient of the permeability in the x-direction/y-direction;

Q = applied boundary flux;

θ = volumetric water content;

t = time.

A heavy rainfall intensity from 15-Sep 2016 to 22-Sep 2016 was observed at Slope A. Therefore, the rainfall data from 15-Sep 2016 to 22-Sep 2016, as illustrated in Figure 13, was used as the flux unit boundary conditions in the seepage analyses for assessing the stability of Slope A. The soil-water characteristic curve (SWCC) and permeability function of the residual soil within Slope A were used as an input for the seepage analyses. SWCC and permeability function of the residual soil at Slope A are shown in Figures 14 and 15, respectively. The SWCC data were obtained from laboratory tests using Tempe cell and pressure plate apparatus. The lines in Figure 14 represent the best-fitted Satyanaga et al. (2017) equation whereas the symbols represent the laboratory test results. The saturated permeability of the residual soil at Slope A as obtained from the laboratory test was 6×10^{-7} m/s. The permeability functions of the residual soil at Slope A was determined indirectly

from SWCC using the statistical model (Childs and Collis-George, 1950) as explained in Fredlund and Rahardjo (1993).

The ground water table on 15-Sep 2016 at 00:00 am as observed from the water stand pipe was 6.6 m and 2.5 m below the ground surface on the crest and toe of the slope, respectively. The initial ground water table in the numerical model was defined based on the readings at these two points. The readings from tensiometers and piezometers were used to set the initial pore-water pressure conditions in the numerical model. The results from the seepage analyses were incorporated into the slope stability analyses using Slope/W (Geoslope International Pte Ltd, 2012a). Slope/W uses the limit equilibrium theory to compute the factor of safety (FOS). Fredlund and Krahn (1977) suggested that Bishop's simplified method was capable of calculating factor of safety with reasonable accuracy. The variations in factor of safety (FOS) during the rainfall period (i.e., from 15-Sep 2016 0:00am to 22-Sep 2016 23:50pm) are illustrated in Figure 16. The FOS of Slope A dropped drastically at $t = 28$ hours (i.e., dropped from 2.7 to 1.46 or dropped around 44.4%) under the heavy rainfall condition. This factor of safety is lower than the allowable factor of safety (1.5) for slope in Singapore (Housing and Development Board, 2010). In other words, $FOS = 1.5$ is classified as a triggering warning value for slopes in Singapore (Housing and Development Board, 2010). Hence, immediate measures could be taken based on the relayed information to ensure the stability of the actual slope on site. In this case, the slope inspection was carried out by engineers as an immediate measure to check the visual condition of slope A. The engineers observed some cracks on the surface of the slope and preventive measures were carried out by filling the cracks using grouting materials in order to avoid rapid infiltration of rainwater into the slope and to maintain the stability of the slope. The results from the stability analyses indicated that field instrumentation results can

be used for the assessment and monitoring of stability of slopes during dry and rainy periods.

7. CONCLUSIONS

- The new slope susceptibility map within the urban area of the residual soil from Bukit Timah Granite in Singapore has been developed. The identification of high risk slopes can be used for the management of slopes in order to prompt preventive works to avoid the damages to nearby residential buildings and public facilities due to slope failures.
- The new slope susceptibility map was developed with the incorporation of unsaturated soil properties based on TRIGRS analyses.
- Field instrumentation can be used for the assessment of slopes with a critical factor of safety close to 1.5 and the planning of appropriate preventive measures. The example of field instrumentation has been provided via comprehensive monitoring of slope A with a critical factor of safety.
- Four types of instrumentation: tensiometer, soil moisture sensor, piezometer and rain gauge, are required for assessment and monitoring of slope stability.
- Tensiometers are installed at shallow depths to monitor the changes of negative pore-water pressures in the slope.
- Soil moisture sensors are installed at shallow depths to monitor the changes of volumetric water contents in the slope.
- Piezometers are installed to observe the changes in the position of groundwater table.
- Rain gauge is installed to measure the rainfall intensity on the observed slope.

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Granite

Zones	k_s (m/s)	Hydraulic diffusivity (m^2/s)	c' (kPa)	ϕ' ($^\circ$)	ϕ^b ($^\circ$)
1	2.00E-07	5.97E-04	7	27.5	20
2	2.84E-05	1.86E-01	7.75	22.25	18
3	6.73E-06	2.08E-02	9.2	28.6	18
4	3.08E-05	2.10E-01	11	27.5	21
5	6.75E-07	4.44E-03	12	30.5	21

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