Slope failures in Singapore due to rainfall

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ABSTRACT

Singapore experienced a number of major and minor slope failures during the months of December 2006 and January 2007 when the island experienced above average monthly rainfalls. Slope failures varied with respect to slope geometry, soil type and rainfall intensity. On 19 December 2006, Singapore experienced the third highest amount of rainfall in 75 years. The relationship between rainfall intensity and slope failures in Singapore is presented in this paper, particularly for the period from December 2006 to January 2007. Initial observations indicated that most slope failures took place when the total rainfall exceeded 200 mm in one day. It was also observed that many slope failures occurred in the residual soil from the Bukit Timah Granite. The roles of soil type and rainfall intensity in rainfall-induced slope failures are explained in detail in this paper.

1. INTRODUCTION

The island of Singapore lies within 15 metres above sea level. Three main rock formations have been observed beneath Singapore residual soil. The Bukit Timah Granite underlies the Bukit Timah nature reserve and the central catchment area in the centre of the island. Sedimentary rocks of the Jurong Formation which contain variations of conglomerate, shale and sandstone are located in southern, southwestern and western part of Singapore. The Old Alluvium forms the eastern part of Singapore.

Climate conditions in Singapore are characterized by uniform temperature and pressure, high humidity and particularly, abundant rainfall. The rainy season of Singapore can be divided into two main seasons, the wetter Northeast Monsoon season from December to March and the drier Southwest Monsoon season from June to September [National Environment Agency, 2007]. During the Northeast Monsoon season, moderate to heavy rainfall usually occurs between December and January, lasting from 1 to 3 days at a stretch. The weather is relatively drier in February until end of March. Maximum rainfall usually occurs between December and January, whereas February and July are noted as the driest months [National Environment Agency, 2007].

This paper discusses the role of soil type and rainfall intensity in rainfall-induced slope failures in Singapore. Unsaturated shear strength parameters are used to study the mechanism of slope failures which occurred mainly in the residual soil of the Bukit Timah Granite. Numerical modelling is performed using Seep/W and Slope/W [Geoslope International Ltd., 2004] to analyze seepage and slope stability in the Bukit Timah Granite residual soils and in the Jurong Formation residual soils with respect to rainfall intensity and soil type.

2. SLOPE FAILURES IN SINGAPORE

Slope failures generally occur in Singapore during the months of December and January. There are many ways in which a slope may fail, depending on slope geometry, groundwater table, soil type, and local environmental factors, such as: rainfall and evapotranspiration. The infiltration of rain water may increase the probability of slope failure, through changes in pore-water pressure inside the slope. Based on meteorological data [National Environment Agency, 2007], the amount of rainfall in December 2006 and January 2007 is above the average monthly rainfall. The average amount of rainfalls for December and January since 1869 are 281 mm and 241.4 mm, respectively. Eleven slopes failed on December 2006 and three slopes failed on January 2007 during heavy rainfall period in Singapore.

Table 1 shows that eleven of the fourteen failed slope are located in the Bukit Timah Granite residual soil. Other slope failures occurred in the Old Alluvium area, such as: Parbury Avenue, Jalan Girang and Chai Chee Road as summarized in Table 1. The geometry of the slope failures is similar in height and angle, except for the slope failure at Jalan Girang where the slope is higher.

Table 1: Slope failures in Singapore between December 2006 and January 2007

No	Location	Date	Soils	Height (m)	Angle(^{o})
1	2 slopes in Marsiling	Dec 2006	Bukit Timah Granite	Average:12	Average: 27
2	Jalan Dermawan	22 Dec 2006	Bukit Timah Granite	18	30
3	Thomson Road	28 Dec 2006	Bukit Timah Granite	12	32
4	Ang Mo Kio St. 21	8 Jan 2007	Bukit Timah Granite	10	30
5	Jalan Anak Bukit	11 Jan 2007	Bukit Timah Granite	15	30
6	4 slopes in Bukit Batok	Dec 2007	Bukit Timah Granite	Average:12	Average: 34
7	KJE near CCK Ave. 4	Jan 2007	Bukit Timah Granite	21	40
8	Perbury Avenue	Dec 2006	Old Alluvium	11	32
9	Jalan Girang	Dec 2006	Old Alluvium	40	33
10	Chai Chee Road	21 Dec 2006	Old Alluvium	6	27

Toll et al. (1999) showed relationships between slope angles and slope heights, taken from 35 slope failures in Singapore (Figure 1). All slope failures in Singapore between December 2006 and January 2007 are also plotted in Figure 1. It can be observed that all failed slopes had a slope angle larger than 27^0. These results confirm Toll et al. conclusions that slopes are unlikely to fail if they have a slope angle less than 27^0.

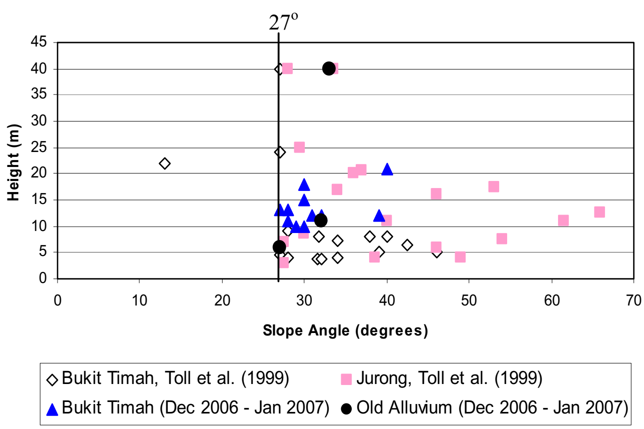


Figure 1: Relationship between slope angle and slope height for slope failures in Singapore

Majority of the slope failures in Singapore between December 2006 and January 2007 were shallow failures. Major slope failures only occurred in Jalan Dermawan and Jalan Girang. On 19 December 2006, a rainfall intensity of 366 mm/day resulted in a slope failure in Jalan Dermawan sending soil, shrub and trees in a 50 m stretch cascading down to Jalan Dermawan [National Environment Agency, 2007]. Landslide of a 40 m high slope at Jalan Girang was observed on 28 December 2006 causing part of a 3 m retaining wall behind a private house to collapse. Although heavy rainfall is common in the months of December and January, this amount of rainfall is noted to be exceptionally high. The rainfall recorded on this day was the third highest in 75 years.

3. ROLE OF RAINFALL AND SOIL TYPE ON RAINFALL-INDUCED SLOPE FAILURES

A study was conducted to observe the role of rainfall intensity and soil type as they seem to be the dominant triggering factors for rainfall-induced slope failures in Singapore. Typical soil profile and shear strength parameters of the Bukit Timah Granite residual soil and the Jurong Formation residual soil were used in the analysis. The percentage of fines, saturated coefficient of permeability and saturated and unsaturated shear strength properties from each residual soil slope are shown in Table 2. Only soil properties of the top 6 m of both residual soil slopes are presented in this paper because rainfall-induced slope failures usually occur in this zone (shallow failures).

The slope angle and height used in the analyses are typical of slope geometry in Singapore, which is 12 m in height with a slope angle of 31°. The slope geometry and the soil classification of each layer for the Bukit Timah Granite and the Jurong Formation residual soil slopes are shown in Figure 2. Typical soil-water characteristic curves (SWCC) and unsaturated permeability functions for the Bukit Timah Granite and the Jurong Formation residual soils are shown in Figure 3a and Figure 3b, respectively.

Table 2: Soil properties of the top 6 m of the investigated slopes

Properties	Bukit Timah residual soil	Jurong residual soil
Total unit weight, γ (kN.m^{-3})	19	18
Liquid Limit, LL (%)	61	43
Plasticity Index, PI (%)	25	22
Fines (%)	55	65
Effective cohesion, c' (kPa)	8	6
Effective internal friction angle, ϕ' (°)	30	28
Angle indicating the rate of increase in shear strength relative to the matric suction, ϕ^b (°)	17	20
Saturated Permeability, k_s (m.s^{-1})	6.45 x 10^{-7}	2.63 x 10^{-8}
Soil Type (USCS)	MH	CL

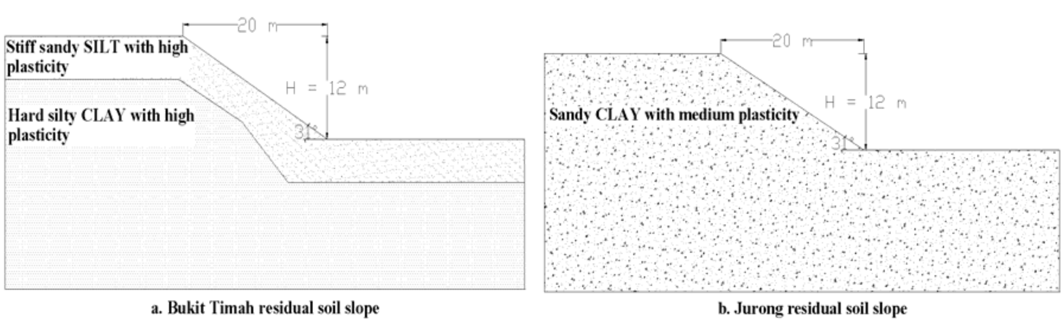
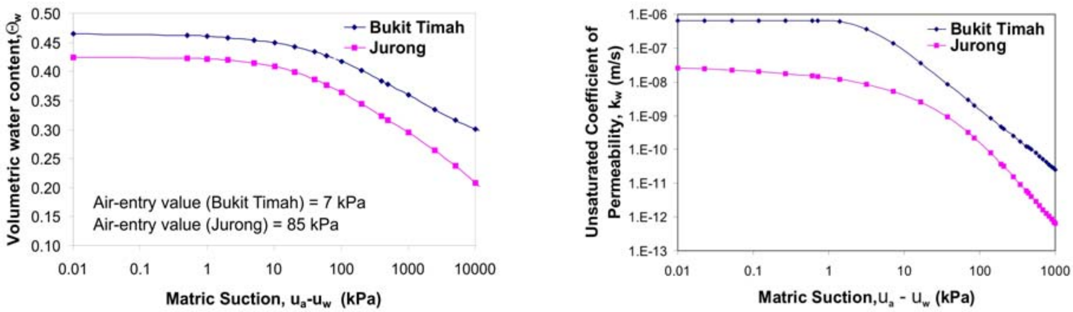


Figure 2: Typical soil profile of the Bukit Timah Granite and the Jurong Formation residual soil slopes

Seepage analyses were performed using Seep/W software in order to observe the changes in pore-water pressure during rainfall. The SWCC and the unsaturated permeability function of the Bukit Timah Granite and the Jurong Formation residual soils together with the rainfall intensity were used in the analyses. The intensity of rainfall used in the analyses was taken from the nearest rainfall station (Ulu Pandan). Figure 4 shows the hourly rainfall intensity used for the seepage analyses. The average rainfall intensity for the first 5 hours was 21.8 mm/hour. After 5 hours of rainfall, the amount of rainfall started to decrease. The rainfall stopped after 29 hours.



a. Soil-Water Characteristic Curves

b. Permeability functions

Figure 3: Unsaturated hydraulic properties of the Bukit Timah Granite and Jurong Formation residual soil slopes

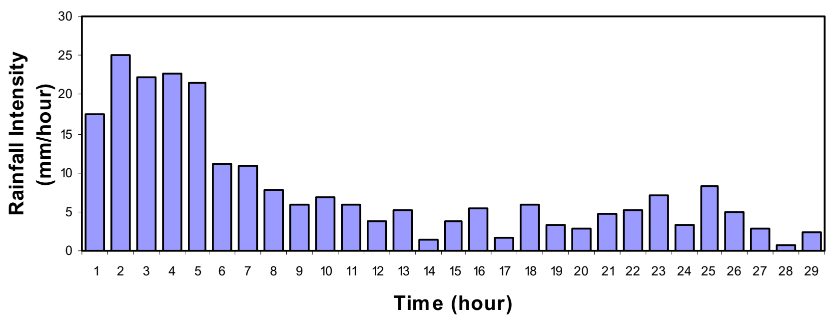
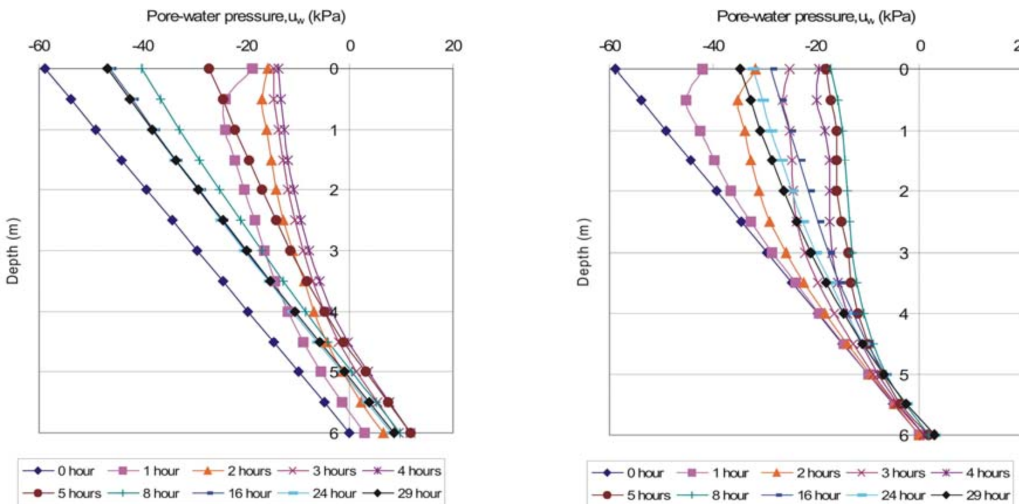


Figure 4: Hourly rainfall intensity used for seepage analyses of typical residual soil slope in Singapore

Pore-water pressure profiles were drawn based on the results of numerical analyses for a location in the middle of the slope (10 m lateral distance from the crest of the slope). Figure 5 shows the development of pore-water pressures with time in the Bukit Timah Granite and the Jurong Formation residual soil slopes during rainfall. Initially, a pore-water pressure of -60 kPa was observed at the ground surface and the pore-water pressure increased with depth. Both residual soil slopes had a similar trend of the initial pore-water pressure conditions. After 1 hour of rainfall, the pore-water pressure increased to -19 kPa near the surface of the Bukit Timah Granite residual soil slope since the rain water infiltrated very fast. The Bukit Timah Granite residual soil has a higher permeability and a steeper permeability function (from -60 kPa up to -10 kPa) than those of the Jurong Formation residual soil, indicating that the rain water could infiltrate at a faster rate through the Bukit Timah Granite residual soil as compared to the infiltration through the Jurong Formation residual soil. Therefore, the pore-water pressure only increased to -42 kPa near the ground surface of the Jurong Formation residual soil slope.

There was a small increase in the pore-water pressure near the ground surface in the Bukit Timah Granite residual soil slope after 2 hours of rainfall as shown in Figure 5 since most of the rain water had already infiltrated into deeper depths. The pore-water pressure reached a positive value of 10 kPa at 6 m depth. This trend continued up to 3 and 4 hours of rainfall. However, after 5 hours of rainfall, the pore-water pressure started to decrease due to the low rainfall intensity. On the other hand, rain water percolated gradually into deeper depths of the Jurong Formation residual soil slope after 2, 3 and 4 hours of rainfall. The pore-water pressure near the ground surface continued to increase until -19 kPa although rainfall intensity had already decreased after 5 hours of rainfall. In the Jurong Formation residual soil slope, the pore-water pressure started to decrease after 8 hours of rainfall, a longer period than that in the Bukit Timah Granite residual soil because of the lower permeability of the Jurong Formation residual soil as compared to the permeability of the Bukit Timah Granite residual soil.



a. Bukit Timah

b. Jurong

Figure 5: Pore-water pressure profiles of the Bukit Timah Granite residual soil slope and the Jurong Formation residual soil slope during rainfall

The pore-water pressures distributions from Seep/W were used as input to the slope stability analyses using Slope/W for the Bukit Timah Granite and the Jurong Formation residual soil slopes. The analyses used the saturated and unsaturated shear strength parameters, c', ϕ' and ϕ^b of the soil. Figure 6 shows the variation of factor of safety with respect to time. Initially, the Bukit Timah Granite residual soil slope had higher factor of safety (1.44) than the Jurong Formation residual soil slope (1.32). After 1 hour of rainfall, the factor of safety of the Bukit Timah Granite residual soil slope decreased drastically to 1.33. The factor of safety continued to decrease significantly until it reached 1.04 around 3 hours of rainfall, indicating failure of the Bukit Timah Granite residual soil slope. This occurred due to the fact that water percolated down very fast through the soil layer until deeper depths, causing a rapid increase in the pore-water pressures in the slope. Meanwhile, the factor of safety in the Jurong Formation residual soil slope decreased gradually to a factor of safety of 1.1 after 4 hours of rainfall. The factor of safety continued to decrease until a marginal value of 1.03 (after 8 hours of rainfall) although the rainfall intensity started to decrease after 5 hours of rainfall (see Figure 4). In other words, the pore-water pressures in the Jurong residual soil slope continued to increase after 8 hours of rainfall.

4. CONCLUSIONS

Seepage and slope stability analyses have been conducted for two types of residual soil in Singapore: the residual soils from the Bukit Timah Granite, and the Jurong Formation. Field observation indicated that majority of slope failures occurred in the Bukit Timah Granite residual soil slope. Results of the analyses demonstrated that rain water infiltrated the Bukit Timah Granite residual soil slope at a faster rate than the infiltration through the Jurong Formation residual soil slope, resulting in the rapid decrease of factor of safety in the Bukit Timah Granite residual soil slope. The differing rates of infiltration could be attributed to the fact that the permeability of the Bukit Timah Granite residual soil is higher than the permeability of the Jurong Formation residual soil. Therefore, the Bukit Timah Granite residual soil slope failed after 3 hours of rainfall whereas the Jurong Formation residual soil slope was marginally safe. In other words, the Bukit Timah Granite residual soil slope is likely to be more prone to failure during heavy rainfalls (>200 mm/day) than the Jurong Formation residual soil slope.

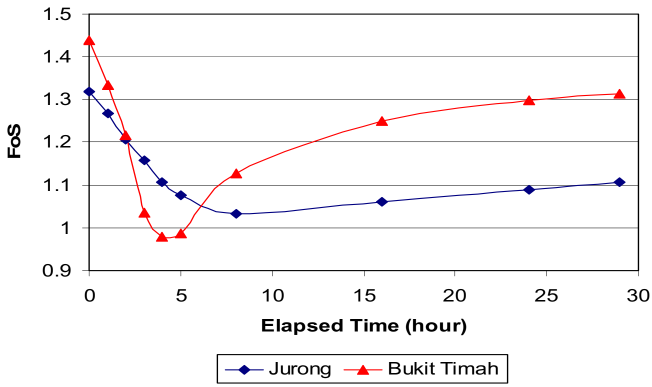


Figure 6: Factor of safety variation during rainfall for the Bukit Timah Granite residual soil slope and the Jurong Formation residual soil slope

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