

# Horizontal Drains in Residual Soil Slopes

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**ABSTRACT:** Horizontal drains have been used extensively for preventive and repair works of slopes. Horizontal drains have been found to be effective in lowering groundwater table to increase the stability of slopes. The ideal location of horizontal drain is at the toe of the slope in order to optimize the thickness of unsaturated zone from the horizontal drain to the ground surface. However, the ideal length of the horizontal drain has not been fully investigated, particularly for residual soil slopes. In this study, the effectiveness of different lengths of horizontal drains in sedimentary and granitic residual soils is investigated. Typical soil-water characteristic curves and permeability functions of the soils were used in performing seepage analyses of water flow through unsaturated soil slope with horizontal drains. It appears that the length of horizontal drain affects water flow through unsaturated soil slope and consequently stability of the slope under heavy rainfall conditions. Results of slope stability analyses indicate that the horizontal drain installed to the critical slip surface provides the ideal length of horizontal drains in residual soil slopes. In addition, soil properties also influence the effectiveness of horizontal drains in maintaining stability of slopes.

**Keywords:** horizontal drains, residual soils, slope stability

## 1 INTRODUCTION

Rainfall-induced slope failures in tropical regions are common problems related to the residual soils subjected to short duration and high intensity rainfalls. Slope failures due to heavy rainfalls were observed in Hong Kong (Brand 1992) and in Singapore (Pitts 1985, Tan et al. 1987, Toll et al. 1999, Chatterjea 1989, Lim et al. 1996, Rahardjo et al. 2001). Being a tropical country, Singapore's climate and geology affect stability of the slopes. Preventive measures are a wise approach for protecting slopes against the possibility of rainfall-induced slope failures.

The function of horizontal drains is to lower groundwater table and it has been recognized as a low-cost means of improving the stability of slope. Horizontal drains had been implemented extensively for preventive and repair works of slopes (Hutchinson 1977, La Rochelle et al. 1977, Lau 1983, Lau & Kenney 1984, Martin et al. 1994).

Many factors affected the effectiveness of horizontal drainage system. The factors include the drain type, location, length and spacing, as well as soil properties and slope geometry. Parameters controlling the horizontal drainage design had been studied by Royster (1980), Lau & Kenney (1984), and Martin et al. (1994). Generally, the effectiveness was de-

scribed in terms of increase in factor of safety as compared to the case without horizontal drains. Locating horizontal drain at the toe of slope in order to optimize the thickness of unsaturated zone from the horizontal drain to the ground surface had been found to give the largest effect on lowering groundwater table (Lau & Kenney 1984, Martin et al. 1994, Rahardjo & Leong 2002, Rahardjo et al. 2003).

However, the ideal length of horizontal drain had not been fully understood, particularly for residual soil slopes. In this study, the effectiveness of different lengths of horizontal drain in sedimentary and granitic residual soils would be investigated.

## 2 FIELD MONITORING

### 2.1 Study Area

The geology of Singapore could be classified into three formations, i.e. igneous rocks of Bukit Timah Granite occupying the center and northwest regions, sedimentary rocks of Jurong Formation in the west region, and a semi-hardened alluvium (Old Alluvium) in the eastern region (PWD 1976). Singapore's climate is favorable to the erosion and weathering processes in the formation of residual soils. Residual soils of the granitic and sedimentary rocks

occupied approximately two-thirds of the land area of Singapore.

Two different slope sites located at Havelock Road and Ang Mo Kio St. 21 in Singapore are used in the parametric studies (Fig. 1). Havelock Road site is located in the sedimentary Jurong Formation and Ang Mo Kio St. 21 site is located in the Bukit Timah Granite residual soil formation.

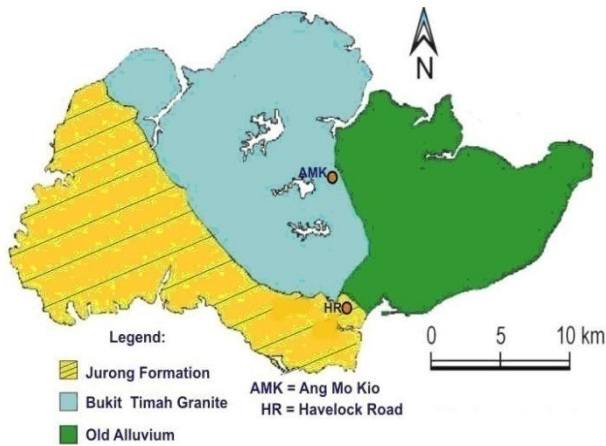


Figure 1. Location of investigated slope in Singapore

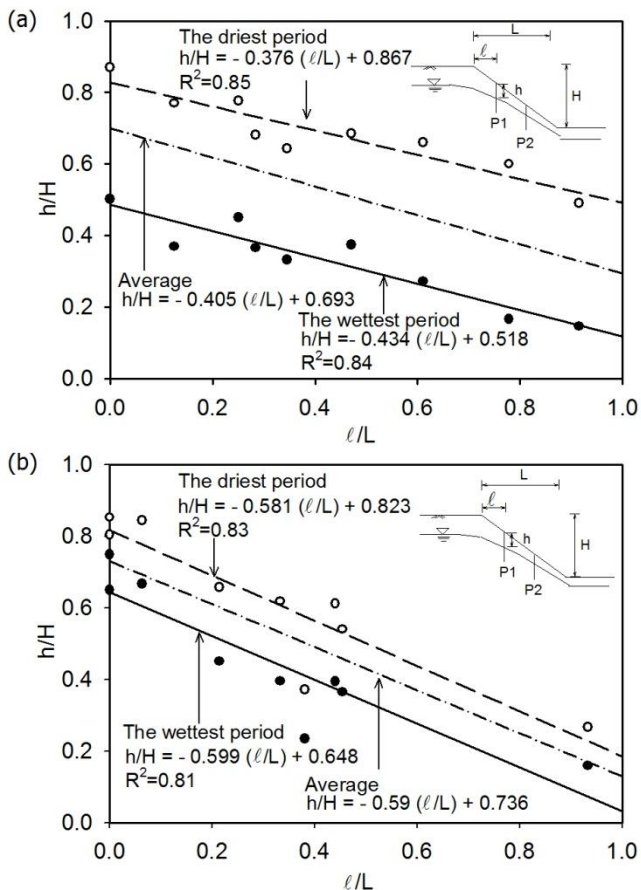


Figure 2. Variation of groundwater table position for: (a) sedimentary Jurong slopes, (b) Bukit Timah Granite slopes

## 2.2 Field Instrumentation and Data Collection

Manual monitoring of Casagrande piezometers for several slopes in Singapore has been carried out for two years, from June 2006 to September 2008. The investigated slopes were instrumented with at least two piezometers installed along the slope to monitor the groundwater table location. During the monitor-

ing period, variations of groundwater table (GWT) positions resulted in certain ranges of GWT for the driest and the wettest periods of sedimentary Jurong Formation slopes as shown in Figure 2(a) and for those of Bukit Timah Granite slopes in Figure 2(b). Symbols  $h$  in Figure 2 represent the depth of GWT from the slope surface, while symbols  $\ell$  correspond to the horizontal distance of the piezometers, P1 and P2, measured from the crest of slopes. Slope heights and slope widths are denoted as  $H$  and  $L$ , respectively. The driest period refers to the period between February and July, while the wettest period is from August to January. The average locations of GWT were drawn to determine typical locations of GWT for residual soil slopes in Singapore.

In the parametric studies (see Sec. 3.11 and 3.21), the maximum position of GWT during the wettest period was assumed to be the initial position of GWT before the installation of horizontal drains. This assumption was made in order to simulate the worst condition of groundwater table that could exist. In general, The GWT position of the sedimentary Jurong Formation slope was found to be deeper than that of the Bukit Timah Granite slope during both the dry and wet periods.

## 3 DESIGNING OF PARAMETRIC STUDY

Two-dimensional seepage analyses were performed using finite element software, SEEP/W (Geoslope International Pte. Ltd. 2004). With the pore-water pressures from SEEP/W, slope-stability analyses were conducted using SLOPE/W (Geoslope International Pte. Ltd. 2004). Parametric studies of the effectiveness of different lengths of horizontal drain in residual soil slopes of Bukit Timah Granite and sedimentary Jurong formations are discussed.

### 3.1 Modelling of Residual Soil Slopes

#### 3.1.1 Slope Geometries

The sedimentary Jurong Formation residual soil slope at Havelock Road has a slope height of 13.71 m and a slope angle of  $24^\circ$  (Fig. 3(a)). The soil observed in the borehole investigation consisted of firm to hard yellowish brown, reddish brown, and white sandy silt with some mica flakes and weathered rock fragments. Test results indicated that the water content, specific gravity, liquid limit, and plastic limit of the soil were 38-40%, 2.65, 61%, and 38.8%, respectively. The soil layer of the slope was classified as sandy silt based on Unified Soil Classification System (USCS) with a unit weight of  $17.5 \text{ kN/m}^3$ , an effective cohesion of  $5 \text{ kN/m}^2$ , an effective friction angle of  $26^\circ$ , and a  $\phi^b$  angle of  $15^\circ$ .

Initial positions of groundwater table in the slope model of parametric studies were obtained from the maximum positions of groundwater table during the

wet period (Fig. 2(a)). Three piezometers were installed in the Havelock Road slope to monitor the position of groundwater table with time. A 14 m-depth of piezometer were placed near the crest of the slope ( $\ell/L = 0$ ), a 10 m-depth of piezometer in the mid-slope ( $\ell/L = 0.35$ ), and a 10 m-depth of piezometer at the toe of the slope ( $\ell/L = 0.94$ ). The depths of groundwater table ( $h$ ), were 6.85, 4.81, and 1.47 m from the ground surface at the crest, mid, and toe slope, respectively.

The Bukit Timah Granite residual soil slope at Ang Mo Kio St. 21 has a slope height of 8 m and slope angle of  $34^\circ$  (Fig. 3(b)). Test results indicated that the water content, specific gravity, liquid limit, and plastic limit range of the soil are 35~40%, 2.64~2.68, 53~66%, and 36~38%, respectively. The soil layer of the slope consisted of clayey silt with a unit weight of  $20 \text{ kN/m}^3$ , an effective cohesion of  $8 \text{ kN/m}^2$ , an effective friction angle of  $33^\circ$ , and a  $\phi^b$  angle of  $25^\circ$ .

Similarly, three piezometers were also installed in the Ang Mo Kio St. 21 slope to observe the groundwater table movement (Fig. 2(b)). The 13, 10, and 6 m-depth piezometers were placed at the crest of the slope ( $\ell/L = 0.10$ ), at the mid-slope ( $\ell/L = 0.50$ ), and at the toe of the slope ( $\ell/L = 1$ ), respectively. The depths of groundwater table ( $h$ ) were about 4.70, 2.79, and 0.39 m from the ground surface at the crest, mid, and toe of the slope, respectively.

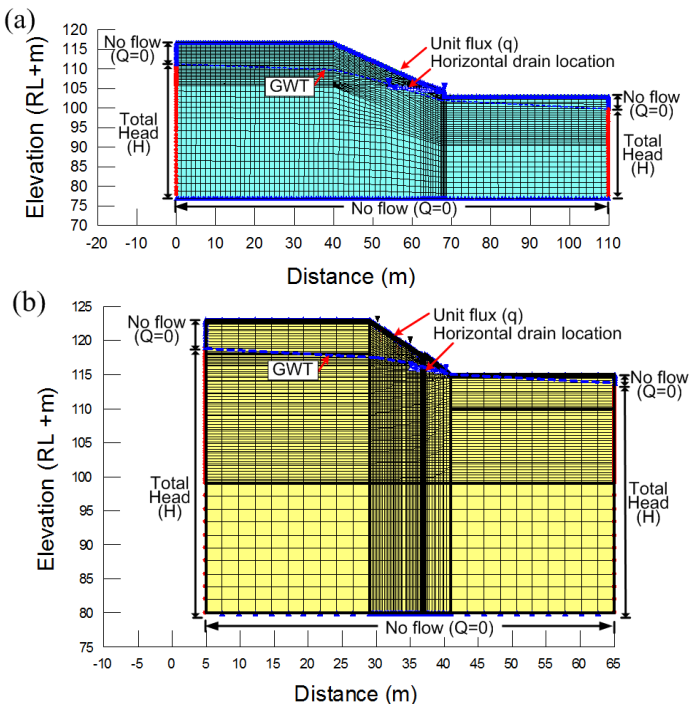


Figure 3. Finite element mesh used in the analyses of: (a) sedimentary Jurong Formation, (b) Bukit Timah Granite residual soil slopes

### 3.1.2 Soil Properties

Figure 4 shows Soil-water characteristic curves (SWCCs) and permeability functions for residual soils at Havelock Road and Ang Mo Kio St. 21. SWCC of the soil in Havelock Road slope was estimated by Fredlund & Xing equation (1994):

$$\theta_w = C(\psi) \frac{\theta_s}{\left\{ \ln \left[ e + \left( \frac{u_a - u_w}{a} \right)^n \right] \right\}^m} \quad (1)$$

where  $\theta_w$  is volumetric water content,  $\theta_s$  is saturated volumetric water content,  $C(\psi)$  is correction factor,  $(u_a - u_w)$  is matric suction (kPa),  $e$  is natural number (2.71828...). Correction factor is taken as 1 as suggested by Leong & Rahardjo (1997), while fitting parameters fitted to experimental data are  $a = 44.25 \text{ kPa}$ ,  $n = 2.37$ , and  $m = 2.1$ . The measured saturated permeability of sandy silt layer for Havelock Road slope was  $2 \times 10^{-7} \text{ m/s}$ .

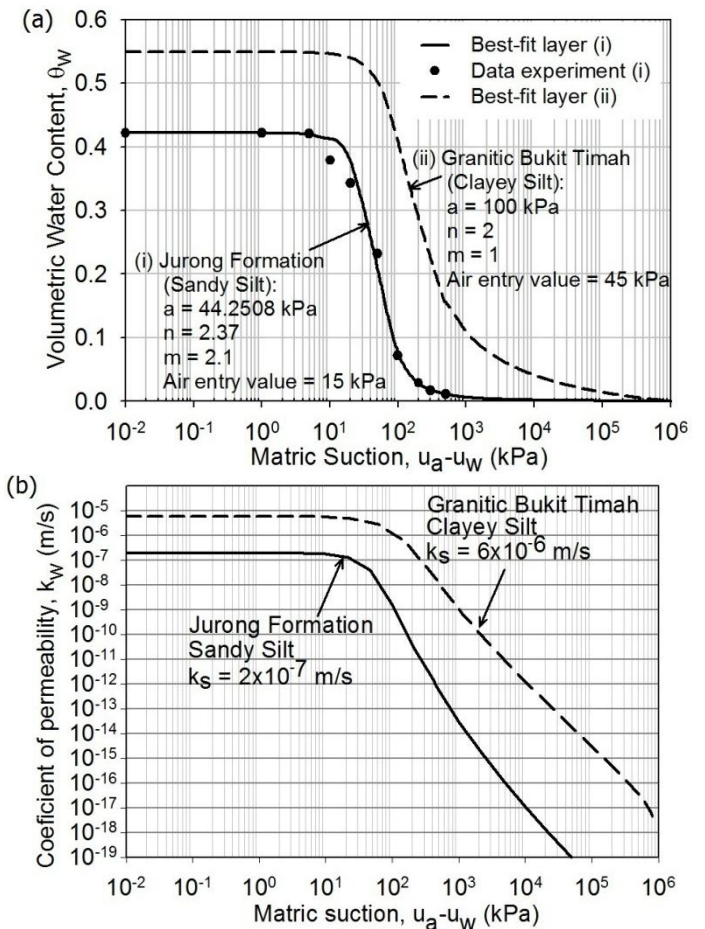


Figure 4. SWCCs and permeability functions of the sedimentary Jurong Formation and Bukit Timah Granite residual soil slopes: (a) SWCCs, (b) permeability functions

SWCC of the soil in Ang Mo Kio St. 21 slope was estimated from the grain size distribution using Fredlund & Xing equation (1994),  $a = 100 \text{ kPa}$ ,  $n = 2$ , and  $m = 1$ . Generally, SWCC for the sedimentary Jurong Formation residual soil at Havelock Road has a lower saturated volumetric water content, a higher air-entry value, and a lower residual water content than the Bukit Timah Granite residual soil at Ang Mo Kio St. 21. The measured saturated permeability of the clayey silt layer of Ang Mo Kio St. 21 slope was  $6 \times 10^{-6} \text{ m/s}$ . The saturated permeability of the Bukit Timah Granite residual soil was higher than that of the Jurong Formation residual soil, indicating

that the Bukit Timah Granite residual soil has larger pore sizes than the sedimentary Jurong Formation residual soil.

### 3.2 Boundary Conditions

The analyses were performed as two-dimensional plane strain problems with 4-noded quadrilateral elements (Fig. 3). Unlike three dimensional computer codes, two dimensional finite element meshes were considered less time consuming to construct and requiring not as much of computer time and space in solving the problem.

The boundary of the slope model was set as three times the height of the slope. Transient process was monitored so that the data from each time step were saved over the transient seepage analyses. Non-ponding function was activated to avoid the excessive accumulation of rainwater on slope surface. On the ground surface, the increment of pore-water pressures was prevented and maximum computed pore-water pressure was limited to be zero. Therefore, surface runoff would occur at the ground surface.

Nodal flux,  $Q$ , equal to zero was applied along the sides of the slope above the water table and along the bottom of the slope to simulate no flow zone. Boundary along the sides of the slope model below the water table was assigned with the corresponding total head,  $h_w$ , of each side. Flux boundary,  $q$ , equal to the desired rainfall intensity and its duration were applied to the surface of the slope. Flux lines were drawn around drains to measure seepage flow per unit length across each flux section.

According to the Code of Practice of Power and Utilities Board (PUB 1992) Singapore for drainage systems, the maximum total amount of rainfall in a day is 533 mm. Therefore, a 22 mm/hr rainfall intensity for 24 hour duration was applied to the slope models in the parametric studies.

The resulting pore-water pressure distribution was calculated in Seep/W and then used to compute the factor of safety of the slope at various time steps in SLOPE/W using the Bishop's simplified method of slices.

### 3.3 Drainage Locations and Designs

Perforated PVC pipes of 100-mm diameter were wrapped in a geo-filter and installed in study areas at 3 m lateral spacing. Horizontal drains located slightly above the toe of slope with the intention of optimizing the thickness of unsaturated zone from the horizontal drain to the ground surface in the parametric studies. The orientation of the drain was not necessarily horizontal. In both soil slopes, horizontal drains were considered to dip downwards at an inclination of  $5^\circ$ .

Different lengths of horizontal drain in sedimentary and granitic residual soils were investigated. Stability calculations were made to determine the critical slip surface. The lengths of drains were designed to be extended to the middle of the slope, to the critical slip surface, and to a distance below the crest of slope, in each type of residual soil slope. Stability analyses were made to determine the location of the critical slip surface which gave initial factor of safety before horizontal drain installation. The critical slip surface for the soil slopes of the sedimentary Jurong Formation and Bukit Timah Granite was determined from slope stability analyses as  $0.83L$  and  $0.67L$ , respectively, which were subsequently used as the lengths of horizontal drains to the critical slip surface. Measured flows from individual drains revealed a wide variation, both in flow rates and their response to rainfall but were usually consistent over time.

In SEEP/W, horizontal drains were idealized as a line of zero flux which was specified internally along the edges of elements and reviewed by maximum pressure. During the iteration process, pore-water pressures along the drain would be adjusted back to zero if its magnitude was positive.

## 4 RESULTS AND DISCUSSION

Homogeneous Bukit Timah Granite and sedimentary Jurong Formation residual soil slope models were subjected to the maximum rainfall of 22 mm/hr for 24 hours. Slope models with different lengths of horizontal drain were analyzed and compared with the slope model without horizontal drain. Therefore, the effectiveness of different lengths of horizontal drain in sedimentary and granitic residual soil slopes could be evaluated. In modelling, the slope height, slope angle, rainfall intensity were kept constant. For different lengths of horizontal drain, the rainfall was applied to the slope after each configuration achieved its equilibrium state.

### 4.1 Sedimentary Jurong Formation Slope

Figure 5 shows the variations of flux rate with time for the different lengths of horizontal drain in the sedimentary Jurong Formation slope. The results show that drains installed to the crest of the slope would be more effective in lowering groundwater level than those installed to the middle of the slope. The horizontal drains discharged a large amount of water as soon as they were installed, indicating that the highest flux rate for horizontal drains installed to a distance below the crest of slope was  $2.5 \times 10^{-6}$  m/s and followed by horizontal drains installed to the critical slip surface ( $1.4 \times 10^{-6}$  m/s). These values would gradually decrease for two years to reach equilibrium state (Fig. 5(a)). On the other hand, the

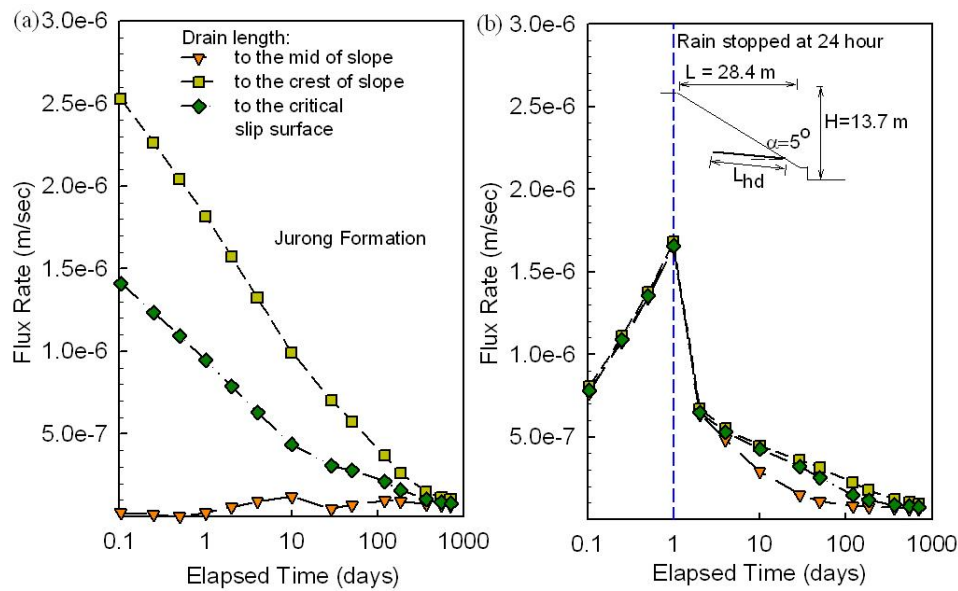


Figure 5. Rate of water inflow to the drain for sedimentary Jurong Formation residual soil slope with different length of horizontal drains: (a) from the horizontal drains installation until reach equilibrium without rainfall to drawdown the GWT, (b) under 22 mm/hr rainfall intensity for 24 hours

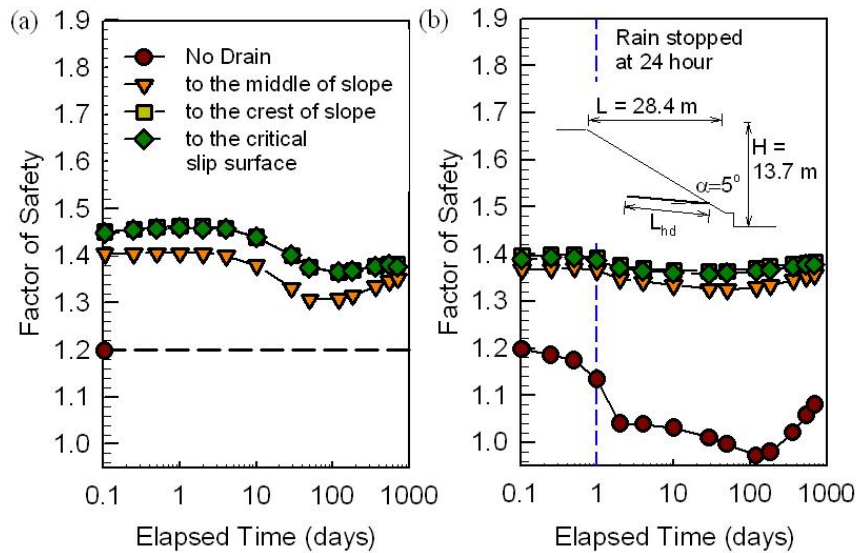


Figure 6. Variation of factor of safety for sedimentary Jurong Formation residual soil slope with different length of horizontal drains: (a) from the horizontal drains installation until reach equilibrium without rainfall to drawdown the GWT, (b) under 22 mm/hr rainfall intensity for 24 hours

flux rate for horizontal drains extended to the middle of the slope was generally consistent about  $1 \times 10^{-7}$  m/s over time. The flow rate of water all the way through the drains would increase during a period of heavy rainfall and decrease slowly after rainfall stopped (Fig. 5(b)). Under an applied rainfall intensity of 22 mm/hr for 24 hours, the maximum flux rates of both configurations of horizontal drains were  $1.7 \times 10^{-6}$  m/s.

Figure 6 illustrates variations in factor of safety with time for the different length of horizontal drains at sedimentary Jurong Formation slope. After installing horizontal drains into the slope, the factor of safety of the slope would improve as the groundwater above the horizontal drain started to be discharged. Subsequently, the factor of safety would gradually decrease due to a significant increase in pore-water pressure near the toe of the slope. This effect was attributed to the groundwater level which was initially lower than the horizontal drain position

at a distance of  $0.4L$  near the toe of the slope, while beyond that point the groundwater was higher than the position of horizontal drain. The groundwater dropped to the drain level at the upper part of the slope, but rose near the toe of the slope, increasing the pore-water pressure near the toe of the slope. The stability of slope decreased before increasing slightly to a steady-state condition (see Fig. 6(a)).

Under an applied rainfall intensity of 22 mm/hr for 24 hours, the factor of safety of the slope without horizontal drain was initially 1.20 and decreased to a minimum value of 0.97 at elapsed time of 120 days as shown in Figure 6(b). The initial factor of safety of the slope with the length of horizontal drain extended to the middle of the slope was 1.35 and the minimum factor of safety was observed to be 1.33 at 26 days after the rainfall stopped. The initial factor of safety of the slope with the length of horizontal drain extended to a distance below the crest of the slope was 1.38 and gradually decreased due to rain-

fall to a minimum factor of safety 1.36 at 5 days after the rainfall stopped. Meanwhile, the initial factor of safety of the slope with the length of horizontal drain extended to the critical slip surface was 1.38 and the minimum factor of safety was observed to be 1.36 at 5 days after the rainfall stopped.

The longer drain would discharge more water from the slope and increase the stability of the slope. However, an attempt to make horizontal drains longer did not appear to show its effectiveness in improving the stability of the residual soil slopes in the sedimentary Jurong Formation.

#### 4.2 Bukit Timah Granite Residual Soil Slope

Flux values from horizontal drains of different lengths as installed in the residual soil slope of the Bukit Timah Granite are presented in Figure 7(a). The results indicated that horizontal drains installed in the slope were effective in lowering the groundwater level and the effectiveness was proportional to

the length of the horizontal drain. Horizontal drains discharged a large amount of water as soon as they were installed as shown by the flux rate (i.e.,  $8.4 \times 10^{-6}$  m/s) for horizontal drains installed to a distance below the crest of the slope and decreased gradually in a short period of time which was 10 days. The flux rate for horizontal drains extended to the middle of the slope was initially  $3.4 \times 10^{-6}$  m/s before decreasing to an equilibrium condition. Meanwhile, the flux rate for horizontal drains extended to the critical slip surface was initially  $5.6 \times 10^{-6}$  m/s before reaching an equilibrium condition. The flux rate of water flowing through the drains would increase significantly during the period of heavy rainfall and gradually decrease after the rainfall stopped (Fig. 7(b)). Under an applied rainfall intensity of 22 mm/hr for 24 hours, the maximum flux was as high as  $7 \times 10^{-5}$ ,  $5.3 \times 10^{-5}$ , and  $3.4 \times 10^{-5}$  m/s for the horizontal drains extended to a distance below the crest of slope, to the critical slip surface, and to the middle of the slope, respectively.

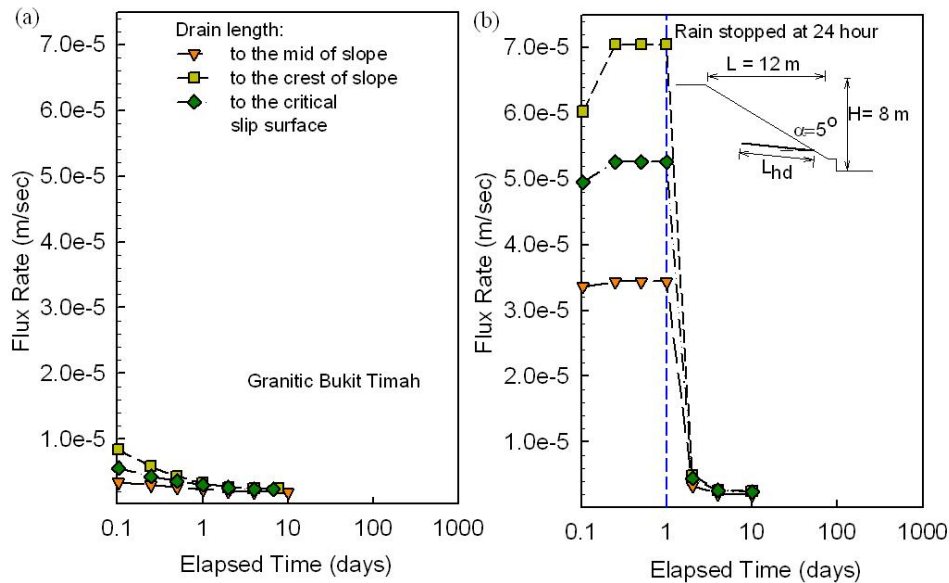


Figure 7. Rate of water inflow to the drain for Bukit Timah Granite residual soil slope with different length of horizontal drains: (a) from the horizontal drains installation until reach equilibrium without rainfall to drawdown the GWT, (b) under 22 mm/hr rainfall intensity for 24 hours

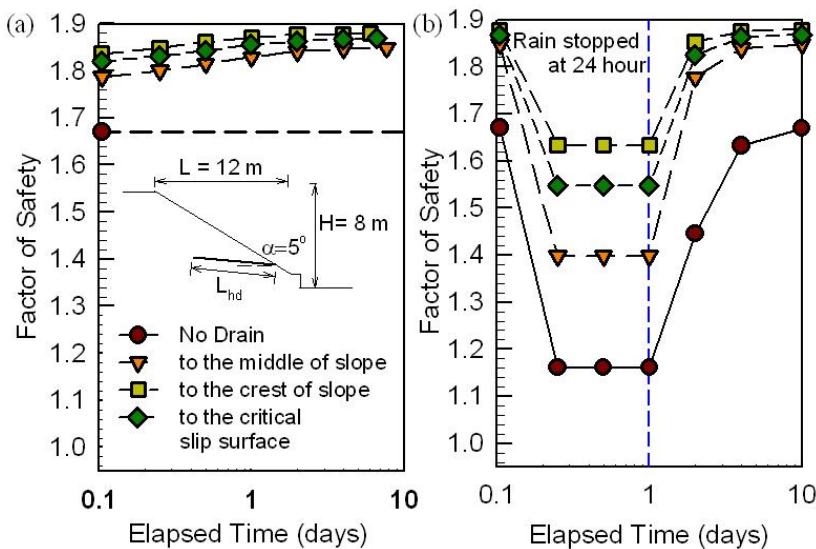


Figure 8. Variation of factor of safety for Bukit Timah Granite residual soil slope with different length of horizontal drains: (a) from the horizontal drains installation until reach equilibrium without rainfall to drawdown the GWT, (b) under 22 mm/hr rainfall intensity for 24 hours

Variations in factor of safety with time for the different lengths of horizontal drains at the Bukit Timah Granite soil slope are shown in Figure 8. After installing the horizontal drains into the slope, the factor of safety of the slope increased slightly and reached equilibrium conditions in a considerably fast rate (see Fig. 8(a)). Only about 10 days was needed for the water to be drained out through the horizontal drain and for the slope to reach its equilibrium condition.

Under an applied rainfall intensity of 22 mm/hr for 24 hours, the factor of safety of the slope without horizontal drain was initially 1.67 and decreased to a value of 1.16 when the rainfall stopped as shown in Figure 8(b).

The initial factor of safety of the slope with the length of horizontal drain extended to the middle of the slope was 1.85 and the minimum factor of safety of 1.40 when the rainfall stopped. The initial factor of safety of the slope with the length of horizontal drain extended to the critical slip surface was 1.87 and decreased rapidly due to rainfall until reaching the minimum factor of safety of 1.55 when the rainfall stopped. Meanwhile, the initial factor of safety of the slope with the length of horizontal drain extended to a distance below the crest of the slope was 1.88 and decreased rapidly due to the rainfall until reaching the minimum factor of safety of 1.63 when the rainfall stopped. The slowest recovery rate of factor of safety occurred in the slope with the length of horizontal drain extended to a distance below the crest of slope, followed by the slope with that to the critical slip surface, to the middle of the slope, and no drain condition. The rates of decreasing and recovery of factor of safety in the Bukit Timah Granite slope were faster than those in the sedimentary Jurong Formation slope due to the saturated permeability of the Bukit Timah Granite residual soil was higher than that of the sedimentary Jurong Formation soil.

Figure 9 presents the percentage of improvement of slope stability in the sedimentary Jurong Formation for the horizontal drain installed to the middle of the slope which is about 13% and to the critical slip surface is 15%. Less additional benefit can be derived from using drains extended beyond where the critical slip surface intersects the top of the slope (15.44%). Figure 9 also illustrates the improvement of slope stability in the Bukit Timah Granite for the horizontal drain extended to the middle of the slope which is about 10.5%, to the critical slip surface is 12%, and for the drains extended to a distance below the crest of slope is 12.5%. Figure 9 explains that a little attempt to extend the horizontal drain length in the residual soil slopes of the Bukit Timah Granite improves the slope stability at about the same percentages as compared to lengthen the longer horizontal drains in the sedimentary Jurong Formation.

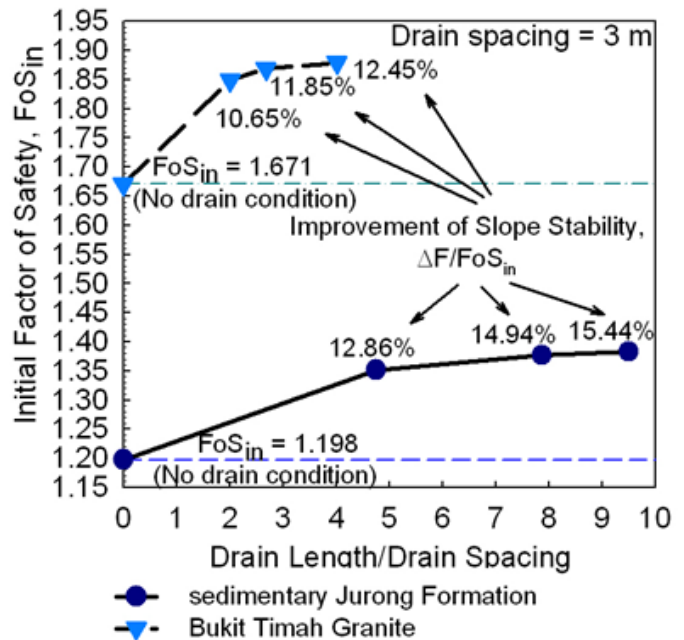


Figure 9. Influence of drain length on stabilizing effect of horizontal drains on sedimentary Jurong Formation and Bukit Timah Granite residual soil slopes

## 5 CONCLUSIONS

The lower permeability of the residual soil of the sedimentary Jurong Formation resulted in a slower change in negative pore-water pressure during rainfall infiltration or lowering of ground water level and therefore, it would take a longer time for the rainwater to penetrate into greater depths as compared to that of the Bukit Timah granitic soils. This condition described why it took about two years to lower down the groundwater level until its equilibrium state in the residual soil slope in the sedimentary Jurong formation. Meanwhile, the higher permeability of the Bukit Timah Granite residual soil played an important role in the rapid development of pore-water pressure in the slopes due to horizontal drain installation and rainfall infiltration.

The factor of safety of the slope slightly increased after horizontal drains were installed into the slope and was significantly faster in reaching steady conditions. No more than 10 days was required for the water to be drained out through horizontal drain and for the Bukit Timah Granite residual soil slope to reach its equilibrium condition.

It has been shown that the length of horizontal drain affects water flow through unsaturated soil slope and consequently stability of the slope under rainfall conditions. The effectiveness of horizontal drain to the slope stability should be also considered based on drain spacing, drain diameter, and drain location. Additionally, soil properties also influence the effectiveness of horizontal drains in maintaining stability of slopes.

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