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Performance of horizontal drains in residual soil slopes

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ABSTRACT: In tropical and subtropical regions, shallow landslides often occur in residual soil slopes. Short-duration, and high-intensity rainfall will increase pore-water pressure. As a result, the shear strength of the soil in the slopes decreases and stability of the slopes is affected. In this study, horizontal drains were installed in a residual soil slope in Singapore in order to improve the stability of the slope. The slope was instrumented with tensiometers and piezometers in order to investigate the effectiveness of horizontal drains as a slope stabilization method against rainfall-induced slope failures. The variations in water table elevation and matric suction in the slope due to rainfall events were monitored. In addition, numerical analyses of the seepage into the slope brought about by the rainfall were carried out, and the results showed a reasonably good agreement with the data obtained from field measurements. The field measurement results indicated that horizontal drains were indeed effective for lowering water table and for increasing the stability of the investigated slope. Therefore, horizontal drains are considered to be a useful and economical method for improving the stability of residual soil slopes against rainfall.

KEYWORDS: horizontal drain, pore-water pressure, rainfall-induced slope failure, residual soil.

1 INTRODUCTION

Rainfall-induced slope failures are common problems in residual soils that have a deep groundwater table in tropical and subtropical regions. Short duration and high intensity rainfalls will increase pore-water pressure, resulting in a decrease in shear strength of soils and eventually affect slope stability. Slope failures due to frequent and heavy rainfalls were commonly shallow slides as observed in Hong Kong (Brand 1992), Malaysia (Liew et al. 2004) and Singapore (Pitts 1985, Tan et al. 1987, Toll et al. 1999, Chatterjea 1989, Lim et al. 1996, Rahardjo et al. 2001). Singapore is located in the tropical
region where heavy rainfalls and high temperatures are conducive for rapid in-situ chemical and mechanical weathering that result in deep residual soil profiles. Because of the climatic conditions and geological features, slope instabilities are common in this region. To protect slopes against the possibility of rainfall-induced slope failures, preventive measures are necessary to ensure the safety of nearby buildings and/or public facilities.

The application of horizontal drains for the lowering groundwater levels is recognized as the most economical method available. In practice, however, these drains must still be regularly maintained and frequently replaced. Horizontal drains have been used extensively for the stabilization of slopes in most countries around the world, such as in Australia (Snowy Mountains Hydro-Electric Authority 1983), Austria (Veder and Lackner 1984, 1985), Brazil (Costa Nunes 1985), France (Pilot and Schluck 1969, Cartier and Virollet 1980, Amar et al. 1973), Great Britain (Hutchinson 1977, Robinson 1967), United States (Smith and Stafford 1957, Royster 1977, 1980; Smith 1980) and Hong Kong (Craig and Gray 1985, McNicholl et al. 1986).

The effectiveness of a horizontal drainage system is governed by several factors, such as drain type, location, number, length and spacing (Kenney et al. 1977, Nonveiller 1981, Lau and Kenney 1984, Nakamura 1988, Martin et al. 1994, Prellwitz 1978), without disregarding the importance of soil properties and slope geometry as controlling parameters. Two dimensional finite element modelling of horizontal drains has been conducted by Choi (1974, 1977), Nonveiller (1981) and Rahardjo et al. (2003) and three-dimensional finite element modelling was carried out by Choi (1977, 1983) and Nonveiller (1981). The effects of rainfall on residual soil slopes were studied by Chipp et al. (1982), Sweeney (1982), Pitts (1985), Krahn et al. (1989), Fredlund and Rahardjo (1993), Lim et al. (1996), Rahardjo et al. (1998), Ng et al. (2003), Li et al. (2005) and Ng et al. (2008) through pore-water pressure measurements using tensiometers and piezometers.

The application of unsaturated soil mechanics for solving seepage and slope stability problems involving residual soil slopes with horizontal drains has not been fully explored in previous studies. Negative pore-water pressure, as a crucial part of the stability of residual soil slopes, needs to be maintained in slopes under varying climatic conditions and taken into account in the design. On the
other hand, rainwater infiltrating the slope surface contributes to the rise in the groundwater table and to the increase in pore-water pressures. Therefore, it is important to install horizontal drains near the toe of the slope to lower the groundwater table (Rahardjo et al. 2003) and consequently, to lower the pore-water pressures. The main focus of this study is to evaluate the role of horizontal drains in increasing the stability of a residual soil slope during heavy rainfall events through measurements of the variations in matric suction in the slope and numerical analyses.

2 FIELD STUDY

The geology of Singapore can be classified into three main formations: (a) the sedimentary Jurong Formation in the west, (b) the igneous rocks of Bukit Timah Granite in the northwest and centre and (c) the semi-hardened alluvium or Old Alluvium in the east (PWD 1976). Residual soils of the granitic and sedimentary rocks occupy about two-thirds of Singapore Island. The instrumented slope studied in this paper consists of residual soils from the Jurong Formation. The Jurong Formation residual soils cover about one-third of the total land area of Singapore. They consist of grey to black interbedded mudstone and sandstone, or reddish sandstone and mudstone conglomerate. Sediments in the form of shale and conglomerates were found in these areas as well (PWD 1976). As a result of tectonic movements, the formation has been severely folded and faulted in the past.

Site Description

The sedimentary Jurong Formation residual soil slope at Havelock Road has a slope height of 13.24 m and a slope angle of 24° (Fig. 1). There is a 1.1 m high of retaining wall at the toe of the slope. The slope surface is well grassed and there are some trees on the right and left hand sides of the observed slope. The investigated area was carefully chosen so that the instrumentation would not be affected by the presence of the trees. There is no previous history of slope failure in this area including during the period of monitoring. Nevertheless, significant high groundwater levels during heavy rainfall were detected through monitoring of piezometers installed at the site. Therefore, rectification work using horizontal drains was implemented to increase the factor of safety of the slope due to its proximity to a residential area.
Five boreholes were drilled at the Havelock Road site. Four boreholes were drilled in the monitored area and used for the installation of inclinometers and Casagrande piezometers after sampling and SPTs. The fifth borehole was used to obtain undisturbed samples for laboratory testing. The soil observed in the borehole investigation around mid-slope consisted of firm to hard yellowish brown, reddish brown and white sandy silt with some mica flakes and weathered rock fragments. The soil of the slope was classified as sandy silt, based on Unified Soil Classification System (USCS), with a unit weight of 17.5 kN/m$^3$, an effective cohesion of 5 kN/m$^2$, an effective friction angle of 26° and an angle indicating the rate of increase in shear strength relative to the matric suction, $\phi^b$ angle, of 15°. The shear strength parameters were determined from multistage consolidated drained triaxial tests at a constant net confining pressure and different matric suctions (25, 50 and 100 kPa) for the sedimentary Jurong Formation residual soil (Fig. 2). The shear strength envelope in Fig. 3 illustrates the decrease in $\phi^b$ from 26° before the air-entry value of the soil (i.e. 15 kPa) to 15° beyond the air-entry value, as the matric suction increases from 0 to 100 kPa. The geotechnical parameters of residual soil from the borehole located at mid-slope are given in Fig. 4. The test results indicate that the water content, specific gravity, the liquid limit, and the plastic limit of the soil were 38-40%, 2.65, 61% and 38.8%, respectively.

2.1 Site Instrumentation and Data Collection

Manual monitoring of measuring devices in the slope were carried out from the end of May 2008 to April 2009 in order to study the response of the residual soil slope to rainfall. Layout of instrumentation at the Havelock Road site is presented in Fig. 5. The measuring devices installed in the slope consist of jet-fill tensiometers, piezometers and inclinometers to provide pore-water pressure, groundwater level data and lateral deformation, respectively. Nine tensiometers and three piezometers were installed in three rows as illustrated in Fig. 5. Lateral deformations of the slope were found to be insignificant, i.e. less than 10 mm, due to the stiffness of residual soils and; therefore, will not be discussed in this paper.

The nine tensiometers were installed in groups of three, placed at depths of 0.47, 1.04 and 1.98 m below ground level and located at the upper, middle and lower sections of the slope, respectively.
Tensiometers were installed in the slope to provide direct measurements of matric suction or the negative pore-water pressure in the soil, particularly during and immediately following rainfall events.

Casagrande piezometers were installed for the continuous monitoring of the groundwater table elevation. The piezometers were installed within the area of the horizontal drains. The installation depths of piezometers at the upper, middle and lower sections of the slopes were 14, 10 and 10 m depth, respectively, with reference to the ground surface level. The piezometer tubes were protected by a lockable PVC pipe, 300 mm in diameter and 500 mm in height, with a cap to prevent vandalism. The Casagrande piezometers were intensively monitored using an electric dip meter to measure the variation in groundwater levels and to check the drain response. In general, measurements were conducted two to three times per week during dry and wet periods. At the same time, pore-water pressure readings were also taken from the tensiometers to monitor their response to the heavy rainfall events. However, there was no monitoring of the surface runoff from the slope.

Rainfall data was collected from a rainfall gauge installed at the Jalan Kukoh site, around 2 km from Havelock Road site. An on-line monitoring system was established at Jalan Kukoh to record data in real time. The rain gauge was connected to a data logger so that rainfall data in real time could be retrieved from a secured website and used in the seepage analyses.

2.3. Horizontal Drainage Design

One row of horizontal drains, 12-18m in length and with a 5° inclination were installed near the toe of the slope to lower the groundwater level. Thirty-three PVC pipes, 100 mm in diameter and containing perforations in the upper half, were wrapped in a geo-filter fabric and installed in the 100-m wide stretch of slope at a lateral space of 3 m. The geo-filter wrapping was necessary to prevent clogging and to ensure the long-term performance of horizontal drains. Rahardjo et al. (2003) suggested placing the horizontal drainage system as low as possible in a slope in order to lower groundwater table. In this case, there was a low retaining wall at the toe of the slope and the horizontal drains were installed 30 cm from the top of the retaining wall.

2.4. Monitoring Results
A set of data from an eleven-month period was compiled from the instrumentation at this site. Data on groundwater level movements were available back to August 2006. The horizontal drains were installed from 12 May to 7 June 2008, starting from the right-hand side of the slope and moving to the left-hand side. The horizontal drains below the instrumented area were installed on 30-31 May 2008. Following the installation of the horizontal drains, tensiometer readings were immediately taken on 31 May 2008 and continuously monitored together with the piezometric levels throughout the eleven-month period following the installation of the drains.

Piezometric monitoring, before and after installation of the drains, indicated that there was a drawdown of the groundwater table due to the installation of the drains (Table 1). It was observed that the horizontal drains could lower the groundwater table in the range of 1 to 4.6, 0.2 to 6.3 and 0.1 to 1.9 m on the crest, middle and toe of the slope, respectively, from the initially high groundwater table between May 2008 (prior to construction of the drains) and April 2009. Flow rate measurements of horizontal drains were immediately performed after their installation to ensure that the horizontal drains worked as designed. It was observed that some of the drains were discharging water and the flow increased due to rainfall. The flow rate of the water monitored two weeks after the drain installation was about 1.1 - 1.7×10⁻⁷ m/s. A regular schedule of maintenance by hydroblasting was recommended to prevent clogging along the horizontal drains, as clogging can affect the drainage performance. Hydroblasting involves the removal of sediment by using a low-pressure, high-volume water jet, since high-pressure water jets will damage pipes and add water into the ground.

Figs. 6 to 8 present the dynamics of the changes in pore-water pressure in response to the heavy rainfall that fell over the eleven months monitored by tensiometers at different depths. Near the crest and middle of the slope, highly negative pore-water pressures reached up to -80 kPa due to evaporation near the ground surface during the dry period, as seen in Fig. 6. During rainfall, the pore-water pressures rose instantly at the shallow depths. Measurements from the days when immediate increase in pore-water pressure occurred indicate that the tensiometers responded well to the heavy rainfall events. Generally, at the depth of 0.47 m below ground level, the measured pore-water pressures in the slope approached zero due to rainfall. Fig. 6 shows that at depths of 0.54 and 1.21 m
below the ground level, positive pore-water pressures up to 10 kPa developed in the crest of the slope after rainfall. Fig. 7 shows that at depths of 0.58 and 1.23 m below the ground level, positive pore-water pressures up to 20 kPa developed in the middle of the slope after rainfall. Meanwhile, at the depths of 0.47 and 1.04 m below ground surface near the toe of the slope (see Fig. 8), there was an indication that the tensiometer positions were close to the horizontal drain elevations so that the pore-water pressures tend to be positive for the first seven months. The negative pore-water pressure less than -20 kPa at the 1.98 m depth near the toe of the slope was due to the fact that the tensiometer position was actually higher than the groundwater table. However, the negative pore-water pressure near the ground surface could be as high as -40 kPa due to evaporation during the dry period from January to February 2009. As soon as the rain fell, the pore-water pressures at the depths of 0.47 and 1.04 m below ground level became positive as the drains discharged water during rainfall, but the pore-water pressure at the depth of 1.98 m remained negative.

Figs. 9 to 11 show the pore-water pressure profiles measured by tensiometers near the crest, the middle and the toe of the slope on 21 August 2008. It can be seen in Figs. 9 and 10 that the pore-water pressure near the crest and the middle of the slope can be as low as -60 kPa and -50 kPa near the ground surface, respectively, during the dry period as measured on 21 August 2008 and tend to be more negative at deeper depths. Maximum changes in pore-water pressure occurred near the ground surface and the magnitude of the changes decreased with depth. Pore-water pressures near the ground surface were the first to be affected by heavy rainfall, followed by those at greater depths. Extended rainfalls caused a significant change in negative pore-water pressure towards positive pore-water pressure as observed for each depth of tensiometer.

Near the toe of the slope, Fig. 11 shows that apparent saturation occurred at depths of 0.47 and 1.04 m due to rainwater infiltration, indicating the presence of water flow in the horizontal drain system which was slightly below the 0.47-m depth tensiometer. Tensiometer at 1.98-m depth remained unsaturated since its position was above the groundwater level.
3 NUMERICAL STUDIES

The SEEP/W finite element code (Geoslope International Pte Ltd 2004) was used to simulate the unsaturated groundwater flow and to determine the pore-water pressure variation with time. Meanwhile, the slope stability analysis was conducted using SLOPE/W (Geoslope International Pte Ltd, 2004b).

3.1 Slope Modelling

A homogeneous slope, rising at 24° to a height of 13.24 m was used as the model for the numerical analyses. The analyses were performed as two-dimensional plane strain problems with 4-noded quadrilateral elements. The slope configuration, horizontal drain location, finite element mesh configuration and boundary conditions are shown in Fig. 12.

The boundary of the slope model was set at three times the height of the slope. The data from each step were saved over the transient seepage analyses. In order to avoid excessive accumulation of rainwater on the slope surface, the non-ponding condition was selected. On the ground surface, surface runoff would occur because the increment of pore-water pressures was prevented and the maximum computed pore-water pressure was limited to zero.

Nodal flux, Q, equal to zero, was applied along the sides of the slope above the groundwater table and along the bottom of the slope geometry to simulate no-flow zone. The boundary along the sides of the slope geometry below the groundwater table was assigned with the corresponding total head, h_w, of each side. The desired rainfall intensity and its duration were applied to the surface of the slope as flux boundary, q. Thin layer finite elements with a high permeability of 2×10^{-4} m/s, were employed to model the horizontal drains. The boundary conditions along the horizontal drains were set to Q = 0 and reviewed by maximum pressure. During the iteration process in SEEP/W, pore-water pressures along the drain would be adjusted back to zero if any of the nodes had a positive pressure.

A seepage analysis was performed on the slope for a heavy rainfall event on 21 August 2008 and the results were then compared with the results from the manual monitoring of pore-water pressure in the slope. The total amount of rainfall on 21 August 2008 was 296.8 mm with a maximum rainfall
intensity of 92.4 mm/hr. The rainfall pattern of 21 August 2008 as shown in Fig. 13 was selected for the numerical analysis because this rainfall resulted in a high increase in pore-water pressure during the wet season. The resulting pore-water pressure distribution was calculated using 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.

### 3.2 Soil Properties of Investigated Slope

Figs. 14 and 15 show soil-water characteristic curve (SWCC) and the permeability function for the sedimentary Jurong Formation residual soil at Havelock Road. The drying SWCC data for the soil on Havelock Road was best-fitted by the Fredlund and Xing equation (1994) from:

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

(1)

where \( \theta_w \) is volumetric water content, \( \theta_s \) is saturated volumetric water content, \( C(\psi) \) is correction factor, \( (u_a - u_m) \) is matric suction (kPa), \( e \) is natural number (2.71828…). Leong and Rahardjo (1997) suggested \( C(\psi) = 1 \). Fitting parameter \( a = 44.2508 \), \( n = 2.37 \) and \( m = 2.1 \) were related to the air-entry value (AEV) of the soil (kPa), the slope of the SWCC and the residual water content, respectively.

The wetting SWCC was used in the numerical analyses since the curve represents increasing water content due to rainfall or adsorption process. The wetting SWCC of the soil was estimated using the simplified model of Feng and Fredlund (1999). The model assumes that the boundary wetting curve and the boundary drying curve were parallel when soil suction was plotted on a logarithmic scale. As a result, only one point on the boundary wetting curve is required to calibrate the model. Parameter \( d \) controls the slope of the curve in the Feng and Fredlund (1999) equation and could be set to the same value for both boundary drying and wetting curves as

\[
w(\psi) = \frac{w_o b + c \psi^d}{b + \psi^d}
\]

(2)

The curve-fitting parameter \( b_w \), for the boundary wetting curve, could be calculated as follows:
\[ b_w = \frac{(w_1 - c) \psi_1^d}{w_u - \theta_i} \]  

(3)

where \( w_u \) is the water content on the boundary drying curve at zero soil suction; \( b, c \) and \( d \) are curve-fitting parameters.; \( \psi_1 \) and \( w_1 \) are the soil suction and the gravimetric water content of the additional point on the boundary wetting curve, respectively; \( c \) and \( d \) are the curve-fitting parameters obtained by fitting the boundary drying curve. The curve-fitting SWCC parameters of the soil used in the seepage analyses were, \( b_w = 6.57 \), \( c = 2.37 \) and \( d = 2.1 \). The measured saturated permeability, \( k_{sat} \), of the sandy silt of the Havelock Road slope was \( 2.1 \times 10^{-7} \) m/s. The saturated permeability was determined by using the rising head field permeability test method (Hvorslev 1951). The wetting SWCC and the saturated coefficient of permeability tests were incorporated into a statistical model to indirectly predict the permeability function.

### 3.3 Seepage Analysis Results

The pore-water pressure and the total head contours were generated using Surfer (Golden Software, Inc. 1997), based on the data measured in the field by the tensiometers before and at the end of heavy rainfall. Pore-water pressure and total head contours obtained from the field measurements before and at the end of heavy rainfall are presented in Figs. 16, 18, 20 and 22. A comparison of pore-water pressure contours obtained from numerical analyses and pore-water pressures obtained from the field before and at the end of heavy rainfall are shown in Figs. 17 and 21. A comparison of total head contours obtained from numerical analyses and total head contours based on measured data obtained from the field before and at the end of heavy rainfall are shown in Figs. 19 and 23.

Generally, it can be seen that the pore-water pressure and total head contours obtained from the field measurement and numerical analysis results before and at the end of heavy rainfall were in reasonably good agreement. Figs. 16 and 17 show that there was the presence of significant matric suctions near the ground surface during the dry period which could affect the stability of the slope. Moisture migration occurred within the slope where water moved upward in the slope, as evaporation, and also across the slope as presented in Figs. 18 and 19. Meanwhile, decreasing matric suctions near the ground surface due to rainfall are shown in Figs. 20 and 21. The total head distributions in Figs.
22 and 23 illustrate that water was flowing along and percolating downward in the slope during the wet period.

Comparisons of the pore-water pressure profiles obtained from the numerical analyses and the field measurements near the crest, the middle, and the toe of the slope are presented in Figs. 24 to 26, respectively. It can be seen from Figs. 24 and 25 that the numerical analyses were able to simulate the process in the field with a reasonably good agreement. The pore-water pressure profiles obtained from the numerical analyses near the crest and in the middle of the slope were very close to the data measured in the field.

The numerical analyses results did not quite agree with the data measured near the toe of the slope (Fig. 26). In the numerical analyses, the initial pore-water pressure profile near the toe of the slope did not match the field data that had a negative pore-water pressure about -15 kPa at a depth of 1.98 m from the ground surface. In the field, the groundwater table was initially lower than the horizontal drain position at a distance of 0.4L (L = horizontal drain length) from the toe of the slope, while the groundwater table beyond that point was higher than the position of the horizontal drain. In the numerical analyses, the initial profile of pore-water pressure was obtained by applying a small uniform infiltration rate to the slope model for a long duration prior to applying the actual rainfall. As a result of establishing the initial conditions for the numerical analyses, the groundwater table dropped to the drain level in the upper part of the slope, but rose near the toe of the slope. However, it appears that in the numerical analyses the pore-water pressures near the toe of the slope built up faster than the actual pore-water pressures in the field which remained negative, causing the discrepancies.

Figure 13 shows the flow rate of horizontal drains from the numerical analyses results normalized by the spacing of the horizontal drains. It can be seen that the flow rate of horizontal drains reached maximum rate at 4.2×10⁻⁷ m/s and was ranged between 1.6-4.2×10⁻⁷ m/s during rainfall event.

3.4 Slope Stability Analysis using SLOPE/W

In the analyses, the sandy silt layers were modeled with and without horizontal drains having a unit weight of 17.5 kN/m³ and measured shear strength parameters: an effective cohesion of 5 kN/m², an
effective friction angle of 26° and a $\phi^b$ angle of 15°. By importing the pore-water pressure distribution resulted from SEEP/W, factors of safety were computed for the slope model with and without horizontal drains in SLOPE/W using the Bishop’s simplified method of slices. The variations of factor of safety with respect to time during heavy rainfall are shown in Fig. 27.

Before heavy rainfall started, the factor of safety of the Jurong Formation residual soil slope without horizontal drains was computed to be 1.27. The factor of safety decreased gradually during rainfall until it reached 1.25 after 21 days of heavy rainfall. The factor of safety subsequently decreased until a minimum value of 1.19 was computed at an elapsed time of 125 days. It is interesting to note that the initial factor of safety 1.27 was considered close to the recommended minimum factor of safety for the slope with a ten-year return period rainfall, i.e. 1.2 (GEO 2007). In addition, the minimum factor of safety did not occur at the end of rainfall, but at a much later time, indicating a possibility of delayed slope failure when factor of safety was equal to 1.

On the other hand, the same Jurong Formation residual soil slope with horizontal drains had a higher initial factor of safety 1.35 and decreased gradually until it reached 1.32 after 21 days of rainfall. The factor of safety continued to decrease to a minimum value of 1.30 at 83 days after the rainfall stopped. Water percolated downward slowly through the Jurong Formation residual soil layer due to its low permeability and as a result, the occurrence of the minimum factor of safety was delayed to sometime later after the rainfall ceased. Some cases of delayed slope failures that took place sometime after rainfall had ended could be explained by the characteristics of factor of safety variation of the Jurong Formation residual soil slope. At all times, the factor of safety of the slope with horizontal drains was higher than the factor of safety of the slope without horizontal drains, indicating that horizontal drains improved the stability of slope, especially during heavy rainfall events.

4 CONCLUSIONS

A good agreement has been found between the numerical analyses and the field data for the pore-water pressure in the sedimentary Jurong Formation residual soil slope which indicates that appropriate modeling parameters have been selected to show the effectiveness of horizontal drains in
slope stabilization. One row of horizontal drains installed near the toe of the slope has been found to be effective in lowering the groundwater table significantly from 0.2 to 6.3 m across the slope. The long-term effectiveness of a drainage system can be verified by extensive monitoring of the reduction in the groundwater level and in the drain discharge with time, especially during heavy rainfall events.

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6 REFERENCES


45) Snowy Mountains Hydro-Electric Authority (1983): Written communication with GCO.


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### Table 1. Groundwater movement monitored in the slope

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<th>Date</th>
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<td></td>
<td>At the crest of the slope</td>
<td>At the middle of the slope</td>
<td>At the toe of the slope</td>
</tr>
<tr>
<td>16 January 2007</td>
<td>4.63</td>
<td>1.23</td>
<td>1.36</td>
</tr>
<tr>
<td>31 May 2008</td>
<td>6.14</td>
<td>3.26</td>
<td>0.95</td>
</tr>
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</table>
| 9 October 2008     | 5.68 | 5.09 | 1.77 | After the horizontal drain installation  
At the end of a heavy rainfall |
| 31 January 2009    | 11.26 | 8.25 | 2.34 | After the horizontal drain installation  
During the dry period. |
Fig. 1. Cross-section of the instrumented slope

Fig. 2. Deviator stress and water volume change versus axial strain curves for the sedimentary Jurong Formation residual soil
Fig. 3. Shear strength of the sedimentary Jurong Formation residual soil with respect to matric suction

Fig. 4. Geotechnical parameters from the boreholes located at mid-slope
Fig. 5. Layout of instrumented slope

Fig. 6. Average pore-water pressure readings at various depths near the crest of the Havelock Road slope (monitoring period: 31 May 2008 to 25 April 2009)
Mid-Slope (Row B) Tensiometer Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth of water table below ground surface (m)</th>
<th>Pore-Water Pressure (kPa)</th>
<th>Rainfall (mm)</th>
</tr>
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<tr>
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<td>-40</td>
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<tr>
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</tr>
<tr>
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<td>5 Oct 08</td>
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<td>10</td>
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<tr>
<td>8 Mar 09</td>
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Fig. 7. Average pore-water pressure readings at various depths on the middle of the Havelock Road slope (monitoring period: 31 May 2008 to 25 April 2009)

Near Slope Toe (Row C) Tensiometer Data

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<th>Depth of water table below ground surface (m)</th>
<th>Pore-Water Pressure (kPa)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
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<tr>
<td>15 Jun 08</td>
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<tr>
<td>8 Mar 09</td>
<td>20</td>
<td>120</td>
<td>400</td>
</tr>
</tbody>
</table>

Fig. 8. Average pore-water pressure readings at various depths near the toe of the Havelock Road slope (monitoring period: 31 May 2008 to 25 April 2009)
Fig. 9. Pore-water pressure profile near the crest of the Havelock Road slope during rainfall (21 August to 11 September 2008)

Fig. 10. Pore-water pressure profile on the middle of the Havelock Road slope during rainfall (21 August to 11 September 2008)
Fig. 11. Pore-water pressure profile near the toe of the Havelock Road slope during rainfall (21 August to 11 September 2008)

Fig. 12. Geometry and boundary conditions of Havelock Road slope
Fig. 13. Rainfall data measured in the slope and normalized flow rate of horizontal drain starting on 21 August 2008

Fig. 14. Soil-Water Characteristic Curve
Fig. 15. Permeability Function
Fig. 16. Pore-water pressure contours (kPa) obtained from the data measured in the field before rainfall.

Fig. 17. Comparison of pore-water pressure contours (kPa) obtained from numerical analyses and pore-water pressure data measured in the field before rainfall.
Fig. 18. Total head contours (m) obtained from the data measured in the field before rainfall

Fig. 19. Comparison of total head contours (m) obtained from numerical analyses and total head measured in the field before rainfall
Fig. 20. Pore-water pressure contours (kPa) obtained from the data measured in the field at the end of rainfall

Fig. 21. Comparison of pore-water pressure contours (kPa) obtained from numerical analyses and pore-water pressure data measured in the field at the end of rainfall
Fig. 22. Total head contours (m) obtained from the data measured in the field at the end of rainfall.

Fig. 23. Comparison of total head contours (m) obtained from numerical analyses and total head measured in the field at the end of rainfall.
**Fig. 24.** Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field near crest of the slope from the beginning of rainfall (t=0) until the end of rainfall (t=21 day).

**Fig. 25.** Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field on the middle of the slope from the beginning of rainfall (t=0) until the end of rainfall (t=21 day).
Fig. 26. Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field near the toe of the slope from the beginning of rainfall (t=0) until the end of rainfall (t=21 day).

Fig. 27. Factor of safety changes of the Havelock Road slope during and after rainfall on 21 August 2008.