Studie of rainfall-induced slope failures

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ABSTRACT: Rainfall-induced slope failures are common problems in steep residual soil slopes in the tropics. The characteristics of water flow, pore-water pressure changes, and shear strength of soils are the main parameters associated with slope stability analysis involving unsaturated soils which are directly affected by the flux boundary condition (infiltration, evaporation) at the soil-atmosphere interface. Procedures for slope stability analyses considering unsaturated-saturated soils as an integral system are presented. The paper also highlights procedures and the importance of characterizing soil properties, flux boundary conditions, spatial and temporal variability of pore-water pressures and instrumentation for slope stability assessment. It has also been shown through examples how these procedures can be used to generate stability assessment charts for local slopes under local environmental considerations.

1 INTRODUCTION

The occurrence of rainfall-induced landslides in residual soil slopes is a problem encountered in many tropical regions with abundant rainfalls. Furthermore, the increasing rate of urbanisation has increased hillside developments for engineered and fill slopes in many regions in the tropics. The analyses of the stability of these slopes involve unsaturated soils because the water table is usually deep. Climatic changes directly affect the unsaturated soil zone. It is important to note that rainfall-induced slope failure involves infiltration through the unsaturated zone above the ground water table. Therefore, a slope should be considered as an integral system of unsaturated-saturated soils in the stability analyses.

The objective of this paper is to outline the basic procedure for assessing stability of residual soil slopes involving saturated-unsaturated soils. The relevant theory and measurements associated with the unsaturated soil for slope stability assessment are briefly introduced. Characterization of soil properties, flux boundary conditions, field instrumentation and interpretation of field measurements for slope stability assessment are discussed through example applications.

2 THEORY

2.1 Stress State Variables

Stress state variables are stress variables that define the stress condition in a soil and it allows the transfer of theory between saturated and unsaturated soil mechanics. There are two independent stress state variables for an unsaturated soil; namely net normal stress, \((\sigma - u_a)\), and matric suction, \((u_a - u_w)\), where \(\sigma\) is total stress, \(u_a\) is pore-air pressure, and \(u_w\) is pore-water pressure. Under a special condition, when a soil is saturated, the pore-water pressure equals the pore-air pressure and the matric suction, \((u_a - u_w)\), diminishes. The stress state variables then revert to a single effective stress, \((\sigma - u_w)\). The stress state variables control the shear strength and volume change behavior of the soil.

2.2 Soil-Water Characteristic Curve

The soil-water characteristic curve (SWCC) relates the water content of a soil to matric suction and it is an important relationship for an unsaturated soil. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions. It has a similar role as the consolidation curve of a saturated soil that relates void ratio or water content to effective stress. The SWCC of a soil dictates the manner by which the permeability, shear strength and volume change of the soil will behave.
at different matric suctions upon drying and wetting (Fredlund and Rahardjo, 1993a).

The SWCC of a soil can be obtained using a pressure plate extractor as shown in Figure 1 and the principle of pressure plate test involving surface tension of water is explained in Figure 2.

### Shear Strength

The shear strength of an unsaturated soil can be expressed in terms of the independent stress state variables as follows (Fredlund et al., 1978):

$$\tau_f' = c' + (\sigma_f - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi_b$$  \hspace{1cm} (1)

where: $c'$ = intercept of the 'extended' Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction are equal to zero (It is also referred to as 'effective cohesion'); $(\sigma_f - u_a)_f$ = net normal stress at failure; $(u_a - u_w)_f$ = matric suction at failure; $\phi'$ = angle of internal friction associated with the net normal stress $(\sigma_f - u_a)$; and $\phi_b$ = an angle indicating the rate of increase in shear strength relative to matric suction, $(u_a - u_w)$.

The extended Mohr-Coulomb failure envelope is defined as a three-dimensional surface tangent to the Mohr circles at failure with the shear stress, $\tau$, as the ordinate and the two stress state variables, $(\sigma_f - u_a)$ and $(u_a - u_w)$ as abscissas. At saturation, the matric suction becomes zero because the pore-water pressure, $u_w$, approaches the pore-air pressure, $u_a$. As a result Equation 1 reverts to the shear strength equation for saturated soils. The extended Mohr-Coulomb failure envelope can be obtained by conducting triaxial tests using a modified triaxial cell (Figure 3) for testing unsaturated soils.

### Permeability

The flow of water through an unsaturated soil can be described by Darcy’s law (Childs and Collis-George, 1950):

$$v_w = -k_w \frac{\partial h_w}{\partial y}$$  \hspace{1cm} (2)

where: $v_w$ = flow rate of water; $k_w$ = coefficient of permeability with respect to the water phase; $\partial h_w/\partial y$ = hydraulic head gradient in the y-direction; $h_w$ = hydraulic head (i.e., the sum of the elevation and pore-water pressure heads or $y + u_w/(\rho_w g)$; $\rho_w$ = density of water; $g$ = acceleration due to gravity.

Because the ability of an unsaturated soil to retain water varies with the matric suction, unlike the saturated zone the coefficient of permeability $k_w$, in an unsaturated zone is not a constant, it is rather a function of matric suctions. The unsaturated water coefficient of permeability can be indirectly estimated.
from the SWCC and the saturated coefficient of permeability, $k_s$. As SWCC can be determined with greater reliability and in a shorter time this indirect method of obtaining the permeability is attractive. Since water can only flow through the water-filled pores, the SWCC therefore, essentially indicates the space available for the water to flow through the soil at various matric suctions. Therefore, the shape of the SWCC can be used to estimate the variation in the water coefficient of permeability with respect to matric suction or the permeability function. Indirect method of obtaining the permeability function is described in detail by Fredlund and Rahardjo (1993b). A permeability function estimated using the SWCC and $k_s$ is shown in Figure 4. Relationship between soil-water characteristic curve and shear strength for a sand and a clayey silt is shown in Figure 5.

\[
\frac{\partial}{\partial x} \left( k_w \frac{\partial h_w}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_w \frac{\partial h_w}{\partial y} \right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t} \quad (3)
\]

where: $x$ and $y$ = cartesian coordinates in the x- and y-direction, respectively; $\rho_w$ = density of water; $g$ = gravitational acceleration; $m_2^w$ = coefficient of water volume change with respect to a change in matric suction ($u_a - u_w$), or the slope of the SWCC.

![Figure 4. Relationship between soil-water characteristic curve and coefficient of permeability for a sand and a clayey silt (from Fredlund & Rahardjo, 1993b)](image1)

![Figure 5. Relationship between soil-water characteristic curve and shear strength for a sand and a clayey silt (from Fredlund & Rahardjo, 1993b)](image2)

2.5 **Seepage Analysis**

Seepage analyses are performed to calculate the pore-water pressure changes in a slope due to rainfall. The governing equation for the flow of water through an isotropic soil can be formulated using Darcy's law as follows (Fredlund and Rahardjo 1993b):

\[
A soil slope can be considered as an unsaturated-saturated soil system. The changing pore-water pressures in the slope under the influence of infiltration can be analyzed using Equation (3). The computed pore-water pressures can then be input to a slope stability analysis, in order to assess the variation in the factor of safety of the slope under different rainfall conditions.

2.6 **Stability Analysis**

Once the possible range of pore-water pressure changes in a slope during a rainfall is established either from seepage analyses or from field monitoring, the stability of a slope can be assessed using the limit equilibrium analyses. The factors of safety with respect to moment equilibrium, $F_m$ and force equilibrium, $F_f$ can be written as follows (Fredlund and Rahardjo 1993b):
where: \( c' \) = effective cohesion, \( \beta = \) sloping distance across the base of a slice, \( R = \) the radius for a circular slip surface or the moment arm associated with the mobilised shear force on the base of each slice, \( N = \) the total normal force on the base of the slice, \( W = \) the total weight of a slice of width \( b \) and height \( h \), \( x = \) the horizontal distance from the centreline of each slice to the centre of rotation or to the centre of the moments, \( f = \) the perpendicular offset of the normal force from the centre of rotation or from the centre of moments, \( \alpha = \) the angle between the tangent to the centre of the base of each slice and the horizontal.

The slope is again treated as an unsaturated-saturated soil system. The \( \phi' \) angle describes the change in shear strength as a result of matric suction changes that can occur during a rainfall. The \( \phi' \) angle is equal to \( \phi \) when the soil is saturated or the pore-water pressure is positive. The \( \phi' \) angle generally decreases when the soil is unsaturated or the pore-water pressure is negative. Both Equations (4) and (5) indicate a decrease in factor of safety as the pore-water pressure, \( u_w \), increases during rainwater infiltration.

3 CHARACTERISATION OF SOIL

Soil properties affect the SWCC, permeability, shear strength and hence the stability of a residual soil slope. Therefore, it is essential to characterize the soil properties for stability assessment. A typical six-grade soil profile characterization for residual soil based on bedrock information and weathering profile condition, proposed by Little (1969) is explained in Figure 6. A comprehensive characterization for a residual soil is illustrated in Figure 7.

Six residual soil slopes were selected for rainfall-induced slope failure studies in Singapore. The locations of the slopes are shown in Figure 8. Yishun, Mandai, NTU-CSE, NTU-ANX and NTU-IHPT93 slopes were intended for comprehensive instrumentation while NTU-FYP slope was selected for small scale point measurement studies. Yishun and Mandai slopes were located in the Bukit Timah granitic formation. The other four slopes were located in the Jurong sedimentary formation. (Figure 8). For illustration, only results from the Jurong sedimentary formation are presented in the subsequent sections.

![Figure 6. Typical weathering profile of residual soil (from Little, 1969)](image)

![Figure 7. Porous saprolite soil from basalt near Londrina, Brazil (from Vargas, 1985)](image)

![Figure 8. Location of the study slopes, generalized geological map of Singapore, schematic diagram of relative position and arrangement of field instruments (from Rezaur, et al. 2002)](image)
Ground investigations were performed in these slopes by drilling boreholes to establish the stratigraphy of the slope, locate the groundwater table and obtain undisturbed soil samples for laboratory testing. At least one borehole was located at both the crest and toe of the slopes. Additional boreholes were drilled on the slope face depending on the length of the slope face and the uniformity of the soil in the slope. At least one of the boreholes was advanced to the depth of the groundwater table or to the bedrock interface to identify the bedrock formation. Continuous undisturbed sampling was performed in each borehole using a Mazier sampler.

By combining the information of both field investigations and laboratory tests, simplified soil profiles were produced to provide convenient reference for soil layering and soil properties at the research slopes. An example of a simplified soil profile for the NTU-CSE slope is shown in Figure 9.

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3.1 Ground investigation results

The variation of index properties with depth and hence with the degree of weathering of residual soils from the Jurong sedimentary formation are shown in Figure 10. This section illustrates how the ground investigation results are assessed for use in the seepage analyses.

3.1.1 Specific Gravity

Specific gravity depends on the mineralogy of soil and it can reflect the history of weathering (Tuncer and Lohnes, 1977). The mineralogy of residual soils varies considerably depending on parent rocks and weathering process. Specific gravity of residual soils from the Jurong sedimentary formation ranges from 2.65 to 2.75 and its value increases slightly with depth (Figure 10). This could be accounted for by the presence of minerals other than Quartz in deeper layers that have a higher specific gravity than Quartz (Aung, 2001).

3.1.2 Void Ratio and Total Density

Weathering leads to a porous structure due to considerable leaching of minerals in the soil. Void ratio appears to decrease with depths (Figures 10) reflecting the variation in the degree of weathering. Water and air replace the soluble minerals resulting in a porous structure. In the upper layers of residual soils, porosity and void ratio are higher therefore water and air phase occupy more space as compared to the lower layers. As a result total density is lower near the surface. At deeper depths, porosity decreases resulting in an increase in total density. Therefore, the variation in total density as well as variation in dry density reflects the variation in degree of weathering. The total density of residual soils from the Jurong sedimentary formations ranges from 1.9 to 2.5 Mg/m³.

3.1.3 Atterberg Limits

In general, plasticity index (liquid limit minus plastic limit) of residual soils decreases with depth as the degree of weathering decreases. In addition, natural water content is very close to or less than plastic limit throughout the depth indicating the unsaturated
condition of the residual soils. However, the decreasing trend of plastic limit and water content with depth is not obvious in the Jurong sedimentary formation (Figure 10). This could be due to less weathering in the soil profiles of the Jurong sedimentary formation at this particular site.

3.1.4 Soil-water characteristic curve & permeability function

The soil-water characteristic curve (SWCC) is a measure of the water storage capacity of soil at various suction values. The ability of a soil to retain water varies with soil suction. Therefore, the coefficient of permeability is not a constant in unsaturated soils but is a function of soil suction because water can only flow through water-filled pores. Suction at which a soil starts to become unsaturated is called air-entry value. The air-entry value of a soil depends on the soil structure. Its value varies with grain size distribution as well as pore size distribution. The coarser the grain size and the larger the inter-particle and intra-particle pores of a soil, the lower is the ability of the soil to retain the saturated condition. When a soil becomes more weathered, more clay minerals are formed and the ability of the soil to retain water under high matric suctions increases or the air-entry value of the soil increases. Therefore, the SWCC of a soil reflects its pore size distribution and hence the degree of weathering.

The SWCCs of the residual soils from different depths of the Jurong sedimentary formation are shown in Figure 11. Figure 11 shows that the saturated volumetric water content and the air-entry value decrease with depth as the degree of weathering decreases or the pore sizes decrease except for the soil from 13-14m depth. This inconsistency may be due to the difference in the parent rock type. The air-entry value of the residual soils from the Jurong sedimentary formation was found to be around 300 kPa. The void ratio varies with depth from 0.5 to 0.2. The permeability functions for residual soils from different depths of the Jurong sedimentary formations estimated using the SWCC of Figure 11 and $k_s$ are shown in Figure 12.

3.2 Shear strength

A summary of shear strength parameters of residual soils from the Jurong sedimentary formations is shown in Table I. The shear strength parameters in general show an inverse relationship with the degree of weathering. While the degree of weathering generally decreases with depth, the shear strength parameters of residual soils appear to increase with depth.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil type</th>
<th>Grade</th>
<th>$c'$ (kPa)</th>
<th>$\phi'$ (°)</th>
<th>$\phi^b$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>Purple Silty Sand</td>
<td>IV</td>
<td>125</td>
<td>42</td>
<td>N.A</td>
</tr>
<tr>
<td>4.5-5.5</td>
<td>Purple Silty Sand</td>
<td>IV</td>
<td>55</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td>9-10</td>
<td>Orange Silty Sand</td>
<td>IV</td>
<td>35</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>22-24</td>
<td>Purple Silty Sand</td>
<td>III</td>
<td>225</td>
<td>50</td>
<td>N.A</td>
</tr>
</tbody>
</table>

The effective cohesion $c'$ of Grade IV residual soils at 3 m to 4 m depths was found to be very high (i.e., 125 kPa) and the corresponding effective friction angle $\phi'$ is 42° (Table I). This could be attributed to the very high bond strength among individ-
ual particles of the weathered rocks of Grade IV. For the weathered rocks between 4.5 m to 5.5 m depths, the effective cohesion decreases to 55 kPa and the effective friction angle increases to 51°. This decrease in effective cohesion and corresponding increase in effective friction angle could probably be due to a change in grain size between these two layers (3−4 m and 4.5−5.5 m depths). The shear strength parameters of Grade IV highly weathered sandstone at 9 m to 10 m depths are lower than those at 4.5 m and 5.5 m depths, perhaps due to a weaker bond strength. The shear strength of Grade III moderately weathered sandstone is very high. The effective cohesion for this weathered sandstone is as high as 225 kPa and the effective friction angle is 50°.

4 FLUX BOUNDARY CONDITIONS

Flux boundary conditions control the response of a slope to climatic changes. Infiltration, runoff, evaporation and subsequent changes in pore-water pressure, shear strength of soil, groundwater table fluctuation and subsurface water movement are influenced by the flux boundary conditions. Therefore, it is important to evaluate these parameters for slope stability assessment.

4.1 Infiltration

Prior to the full-scale instrumentation of a slope it is desirable to have a preliminary qualitative understanding of the infiltration capacity and transient response of matric suction to an advancing wetting front in the instrumented slopes. This could be achieved by performing a double-ring infiltration test in conjunction with a few quick draw tensiometers as shown in Figures 13 and 14. The layout of the infiltrometer and tensiometers is shown in Figure 15. The study can be performed on a vegetated and a bare surface simultaneously. Results from such experiments on a flat grass-covered surface are shown in Figure 16. Figure 16a shows the cumulative infiltration rate at various times obtained from the double-ring infiltrometer test. Figure 16b shows the response of the tensiometers at different depths to the advancing wetting front. Such tests are useful to assess the infiltration rate and permeability of the soil at shallow depths. For example, from the response time of the tensiometers to the infiltrating water at two different depths (Figure 16b) it is possible to calculate the velocity of water movement in the vertical direction. The permeability of the soil can be calculated from Darcy's law.
It is not always feasible to conduct a detailed and full-scale comprehensive field instrumentation for long-term monitoring because of budget constraints. Under such circumstances point measurements with simulated rainfalls can be performed. Such studies although are not comprehensive and lack the features of a full-scale study can still provide meaningful results from small plots within a short time. Such rainfall simulations speed up the process of data collection, as it is not necessary to wait for a natural rainfall. The installation of tensiometers can be confined to a small plot \((1 \times 1 \text{ m}^2)\) as shown in Figure 17 rather than covering the entire slope. Results from a point measurement study on a small plot with simulated rainfalls at the NTU-FYP slope are shown in Figure 18.

![Figure 16](image16.png)

(a) Cumulative infiltration versus time

![Figure 17](image17.png)

(b) Matric suction versus time

Figure 16. Cumulative infiltration rates from a double-ring infiltration test on a flat grass-covered surface and tensiometer responses at various depths to the advancing wetting front due to infiltration (from Kumar & Ganesh, 1996)

Figure 17. Small scale point measurements with simulated rainfall (from Teo & Yap, 1993)

![Figure 18](image18.png)

Figure 18. Typical results from small scale point measurement studies at NTU-FYP slope. Illustration shows total head variations with time at different depths subjected to a simulated rainfall of 196 mm h\(^{-1}\) for a period of 32 minutes (from Teo & Yap, 1993)

4.2 Runoff

Field tests can also be carried out on the instrumented slopes in order to measure the infiltration characteristics on a slope surface. The rainfall-runoff-infiltration characteristics of a slope can be studied on an isolated plot of the slope (Figure 19). The runoff is measured using a calibrated flume with a capacitance water depth probe (Figure 20). The study can be conducted under a simulated rainfall using sprinklers (Figure 19) or a natural rainfall. The uniformity in rainfall application (simulated) can be assessed by collecting rainfall in a number of small cans spread randomly over the area and comparing the rainfall collected in the cans for a fixed period of rainfall application.
Figures 21 and 22 show the runoff hydrograph from a simulated and a natural rainfall, respectively. Such runoff measurements and hydrographs allow for indirect assessment of total infiltration into the slope resulting from rainfall events. The infiltration rates shown in Figure 21 were derived as the difference between rainfall and runoff rates assuming interception losses to be negligible. Such hydrographs resulting from several rainfall events can then be used to assess infiltration into a slope as a percentage of rainfall amounts as shown in Figure 23. In Figure 23, infiltration (as a percentage of total rainfall) is plotted against rainfall amount records from natural rainfalls monitored in the NTU-CSE slope. It appears from Figure 23 that rainfall events which produce small total amount of rainfall may contribute fully to infiltration.

Figure 23 also suggests the existence of a threshold rainfall amount. Any rainfall below this amount will not produce any runoff and the whole rainfall may end up as infiltration. With reference to Figure 23 (dotted line) this threshold appears to be about 10 mm of total rainfall. Beyond the threshold rainfall, the percentage of rainfall contributing to infiltration decreases with increasing total rainfalls. The infiltration amount could decrease to about 40% of the rainfall (Figure 23) for rainfall events producing a higher total amount. This however, does not mean that the total infiltration amount is less with rainfall events producing high total rainfall than rainfall events producing small total rainfalls. For example, with 40% of the rainfall contributing to infiltration a 100 mm rainfall (higher total amount) would result in 40 mm total infiltration. While with 100% of the rainfall contributing to infiltration a 10 mm rainfall would produce only 10 mm of total infiltration.

The data suggest that in residual soil slopes total infiltration could range between 40% to about 100% of the total rainfall depending on the rainfall amount. The relationship (Figure 23) derived from the rainfall records in the residual soil slope has practical significance. If the rainfall amount is known, Figure 23 could indicate the fraction of the rainfall that could become infiltration. This information can then be used in seepage analyses as flux boundary conditions.
4.3 Evaporation

Evaporation from a slope also plays an important role in matric suction recovery. Potential evaporation from a slope can be measured using a Penman pan shown in Figure 24. However, the actual evaporation depends on the negative pore-water pressure near the soil surface (Figure 25).

5 INSTRUMENTATION

Instrumentation is an important aspect of stability assessment against rainfall-induced slope failures. The instruments involved are a rain gauge, piezometers and tensiometers for measuring positive and negative pore-water pressures, respectively. A schematic diagram of relative position and arrangement of field instruments in one of several instrumented slopes in Singapore is shown in Figure 8.

The mechanism of water flow within a slope during evaporation and infiltration can be observed through continuous real-time monitoring of the pore-water pressure and rainfall events as illustrated in Figure 26a. The groundwater table plays an important role in governing the suction profile in the deeper soil layers. Typical results from piezometer readings in conjunction with rainfall at the NTU-CSE slope are shown in Figure 26b. The pore-water pressure distribution can then be used to assess the stability of the slope over a period of time (Figure 27).
The effect of soil cover can also be studied from the instrumented slopes. Figure 28 shows the responses of NTU-IHPT93 slope under three different surface covers to the same rainfall events. The effect of vegetation on negative pore-water pressures in a slope can be observed from the cyclic pattern of the pore-water pressure within the root zone of a tree (0–1.4 m depth) as illustrated in Figure 29.

Spatial and temporal variability in data causes difficulty in representing the soil profile with a deterministic or a precisely defined set of hydraulic parameters. Time series of pore-water pressure data from an instrumented slope can also be used to examine the spatial and temporal variability in pore-water pressures across the slope profile as shown in Figure 30. Using autocorrelation analyses the 'range' (a measure of the length of influence, for

![Figure 27. Variation in factor of safety with time and rainfall (from Rahardjo et al., 2000)](image)

![Figure 28. Changes of in situ total head profiles in response to rainfall under different conditions of slope cover (from Lim et al., 1996)](image)

![Figure 29. Effect of a Rain Tree on pore-water pressures (from Gasmno et al., 1999)](image)

![Figure 30. Distribution of range and sill parameters along the slope length and depth in NTU-CSE slope (from Rezaur et al., 2002)](image)
time series data) and 'sill' (a measure of temporal variability, for time series data) were calculated for the time series of pore-water pressures in NTU-CSE slope. The spatial distribution of range and sill across slope length and depth are shown in Figure 30.

6 ASSESSMENT OF SLOPE STABILITY

A parametric study was performed to examine the effect of infiltration on the stability of unsaturated residual soil slopes by Rahardjo et al. (1999, 2000). A finite element seepage program, SEEP/W (Geo-Slope, 1998a), was used to simulate rainwater infiltration into a slope and generate transient pore-water pressure distributions for different combinations of slope angle and height. The limit equilibrium slope stability model, SLOPE/W (Geo-Slope, 1998b), was then used to determine the critical slip surface and the factor of safety for the transient pore-water pressure distributions calculated by SEEP/W. This provided information about the effect of infiltration on slope stability. The results from the parametric study were used to develop charts to provide preliminary assessments of slope stability against rainfall-induced slope failure for typical residual soil slopes in Singapore.

In the parametric study a combination of four different slope angles of 18°, 27°, 45°, 63° (3H:1V, 2H:1V, 1H:1V, 0.5H:1V) and three different slope heights of 10, 20, and 40 m were analyzed. A generalized geometry of the slope model used in the parametric study is shown in Figure 31. The slope material was assumed to be homogeneous, single layered with a saturated permeability of $1.0 \times 10^{-4}$ m s$^{-1}$. The shear strength properties of the slope material are given in Table II. The SWCC and the permeability function are shown in Figures 32 and 33, respectively.

![Figure 31. Generalized geometry of slope model for parametric study (from Rahardjo et al., 2000)](Image)

![Table II. Shear strength parameters for the parametric study](Table)

<table>
<thead>
<tr>
<th>Combination</th>
<th>$c'$ (kPa)</th>
<th>$\phi'$ (deg)</th>
<th>$\phi$$_b$ (deg)</th>
<th>$\gamma$ (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>26</td>
<td>26</td>
<td>20</td>
</tr>
</tbody>
</table>

![Figure 32. Soil-water characteristic curve of residual soil from Jurong sedimentary formation (from Rahardjo et al., 2000)](Image)

![Figure 33. Permeability function computed from the drying soil-water characteristic curve of Figure 33 (from Rahardjo et al., 2000)](Image)

The initial pore-water pressure distribution for each slope configuration was defined as a hydrostatic pore-water pressure profile with a limiting negative pore-water pressure of 75 kPa. This limit was selected based on field measurements of negative pore-water pressures. The top boundary was specified as a flux boundary. A rainfall intensity of 80 mm hr$^{-1}$ ($2.2 \times 10^{-3}$ m s$^{-1}$, a typical rainfall rate during heavy rainfalls in Singapore) was applied from time equal to 0 hour until time equal to 4 hours. A rainfall intensity of about zero ($1.0 \times 10^{-12}$ m s$^{-1}$) was then applied for a further period of 10 days to allow the water that infiltrated into the slope to redistribute. The top boundary condition and all other parameters (except slope angle and height) were the same for all analyses.
The results from the seepage analyses of the parametric study show that the slope height, slope angle and the transient pore-water pressure distribution influence the stability of a slope. Infiltration characteristics were similar for each of the slopes. Examples of pore-water pressure and hydraulic head distribution in a slope (angle 27° and height 10 m) after four hours of rainfall are shown in Figures 34a and 34b, respectively.

Figures 35a and 35b show the critical slip surface for the 10 m, 27° slope before the rainfall event (i.e., time equal to 0 hours) and after four hours of rainfall. The critical slip surface was located at a depth of about 9.4 m at time equal to zero hour (Figure 35a) and the factor of safety was about 2.9 (Figure 35b).

The factor of safety and the respective depth of critical slip surface over time for 27° slopes with different heights are shown in Figures 36a and 36b, respectively. A few trends are apparent from these plots. Prior to the commencement of rainfall, slopes with lower heights had a higher factor of safety (Figure 36a) and the depths of critical slip circles are deeper for slopes with greater heights (Figure 36b). As rainfall continued, positive pore-water pressures developed (between 1 and 4 hours) and these trends changed.

Both the stability and the depth of critical slip surface decreased over time during rainfall due to infiltration and reached minimum values at the end of four hours, and increased over time during pore-water pressure redistribution (between 4 and 28 hours, see Figures 36a and 36b). It is also evident that after the development of positive pore-water pressures (time = 4 hours) due to infiltration, all 27° slopes regardless of their heights had about the same factor of safety and the same depth of critical slip
surface. This implies that once positive pore-water pressures have developed, slope height has little effect on the factor of safety and the depth of critical slip surface.

These examples show that the transient pore-water pressure distribution appears to be a key triggering mechanism behind rainfall-induced slope failures. Infiltration may lead to the development of positive pore-water pressure zones in a slope. After a period of time when the positive pore-water pressure zone has developed, the critical slip surface of the slope becomes shallow passing through the positive pore-water pressure zone.

The results of the parametric study were used to develop preliminary assessment charts for slope stability against rainfall. As an example for a typical residual soil slope in Singapore of 10 m height and slope angle of 27°, the assessment charts are shown in Figure 37. Figure 37a shows the transient pore-water pressure distributions in the slope subjected to a rainfall of 80 mm hr$^{-1}$ for different duration. Figures 37b and 37c show the respective factors of safety for different slope angles and heights, respectively.

Figure 36. Time series of factor of safety and depth of critical slip circle during rainfall and redistribution for a 27° slope (from Rahardjo et al., 2000)

(a). Factor of safety

(b). Depth of critical slip circle

Figure 37. Charts for preliminary assessment of slope stability (from Rahardjo et al., 2000)
7 CONCLUSIONS

Slope responses to rainfall, infiltration and evapotranspiration processes are variable in space and time and are largely influenced by the dynamic climatic conditions, soil properties and vegetation. Instrumented slopes can provide an understanding of slope responses to such processes over a long-time which is essential for advancing rainfall-induced slope failure studies.

Slope stability against rainfall should be analyzed as a dynamic problem involving environmental changes instead of a static problem as conventionally considered. The unsaturated soil zone is the crucial interface between environment and the slope and unsaturated soil mechanics principles can be used for realistic assessment of slope stability against rainfall. The slope itself should be analyzed as an integral system of unsaturated-saturated soil where saturated soil is a special case of unsaturated soil.

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