Unsaturated Soil Mechanics for Slope Stabilization

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ABSTRACT: Rainfall-induced slope failures commonly occur in the unsaturated zone above groundwater table in many steep residual soil slopes. During a rainy season, desiccated soils with higher permeabilities will increase rain infiltration into slopes causing an increase in pore-water pressures in the zone above the groundwater table. In addition, the groundwater table may rise to result in a further increase in pore-water pressures. As a result, the shear strength of the soil will decrease and factor of safety of the slope can decrease to below a critical value, triggering slope failure. Therefore, it is important to be able to protect unsaturated soil zone within a slope by controlling the groundwater level and the flux boundary conditions across slope surface as a slope stabilization method. In this paper, the mechanisms for maintaining unsaturated zone in a slope using several slope stabilization methods are described using field examples involving site investigation, numerical analyses and instrumentation. The effectiveness of each slope stabilization method is assessed using principles of unsaturated soil mechanics.

1. INTRODUCTION

Global warming accompanied with more rainy days with higher rainfalls over a shorter time scale is a major concern around the world. Numerous slope failures occur in steep residual soil slopes with a deep groundwater table during rainfalls. A significant thickness of unsaturated soil zone above the groundwater table is a general characteristic of steep residual soil slopes (Figure 1). An unsaturated soil can be defined as a soil which has four phases (i.e., solid, water, air, and contractile skin) and the pore-water pressure is negative relative to the pore-air pressure (Fredlund and Rahardjo, 1993). The negative pore-water pressure in unsaturated soil is highly influenced by the flux boundary condition changes (i.e., infiltration, evaporation and transpiration) resulting from the variation in climatic conditions. On the other hand, the negative pore-water pressure contributes additional shear strength to the unsaturated soil. As water infiltrates into the slope, pore-water pressure in the slope increases (matric suction decreases), and the additional shear strength due to matric suction will decrease or even disappear, causing the slope to be more susceptible to failure. Evaporation and transpiration will restore the loss of matric suction in the slope and this climatic variation occurs at all times. In other words, the unsaturated zone is a dynamic interface of the slope with the environment and as a result, factor of safety of slope is affected dynamically by climatic changes.

Slope failures in residual soils are likely to occur due to several factors, such as geological activities, hydrological influence, topographical features, weathering processes, human interference, vegetation and climatic conditions (Sower, 1992; Broms and Wong, 1991 and Brand, 1984). 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; Chatterjea, 1989; Lim et al., 1996; Toll et al., 1999; Rahardjo et al. 2001). 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, 2008) and Li et al. (2005) through pore-water pressure measurements using tensiometers and piezometers. 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 or public facilities.

Horizontal drains for lowering groundwater levels are recognized as the most economical method available. Horizontal drains for the stabilization of slopes have been used extensively 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; Amar et al., 1973; Cartier and Virollet, 1980), Great Britain (Robinson, 1967; Hutchinson, 1977), United Sates (Smith and Stafford, 1957; Royster, 1977, 1980; Smith, 1980) and Hong Kong (Craig and Gray, 1985; McNicholl et al., 1986). Many researchers studied the effectiveness of horizontal drains in improving the stability of slope by modeling the horizontal drain using finite element analyses. 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).

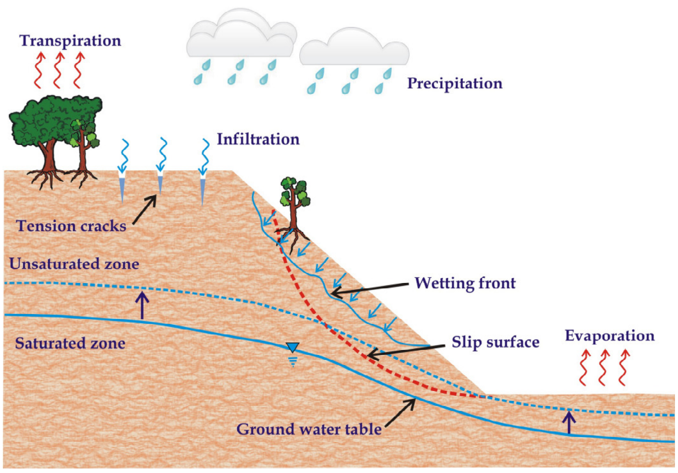


Figure 1 Mechanism of rainfall-induced slope failure
(after Rahardjo et al., 2007)

Capillary barrier system is constructed as a surface cover for a slope in order to minimise rainfall infiltration into the slope. A capillary barrier is an earthen cover system using a fine-grained layer of soil overlying a coarse-grained layer of soil (e.g. Ross, 1990a,b; Stormont, 1996). Previous research works have indicated the effectiveness of the capillary barrier system as a soil cover in reducing rainfall infiltration (Stormont, 1996; Morris & Stormont, 1997a,b; Khire et al., 2000; Tami et al., 2004a,b). In the case of a slope with a high groundwater table and is prone to rainfall-induced slope failure problems, capillary barrier system can be installed together with horizontal drains.

Conventional slope protection systems sometimes can be costly, difficult to construct and may not fit in with the site aesthetics. Use of vegetation or green technology is an alternative technique that combines biological elements and engineering (bio-engineering) design methods to improve slope stability and erosion control (Endo and Tsuruta, 1969; Burroughs and Thomas, 1977; Greenway, 1987; Coppin and Richards, 1990; Gray and Sotir, 1996; Montgomery et al., 2000; Norris & Greenwood, 2000). Figure 2 shows the effect of vegetation on the water flow within slope surface.

Chok et al. (2004) incorporated vegetation-dependent parameters, apparent root cohesion (c_R) and depth of root zone (h_R), into their finite element slope stability analysis. The results show that vegetation plays an important role in stabilising shallow-seated slope failure, and significantly affects stability. Tsukamoto (1990) studied the effect of tree roots on debris slides for steep forested slopes of Japan and concluded that the effect of vertical roots is to lower a potential sliding plane to the deeper and harder soil profile. Schwarz et al. (2010) studied the effect of vegetation on slope stability by incorporating lateral root reinforcement in slope stability analysis. They found that lateral root reinforcement can strongly influence the stability of slopes up to a certain area (1000–2000 m^2). The magnitude of this stabilizing effect depends on parameters such as inclination, soil mechanical properties, and root distribution. Mafian et al. (2009) studied the effects of roots on soil strength and suction. They found that root reinforcement can be used as a bio-engineering solution for slope stability.

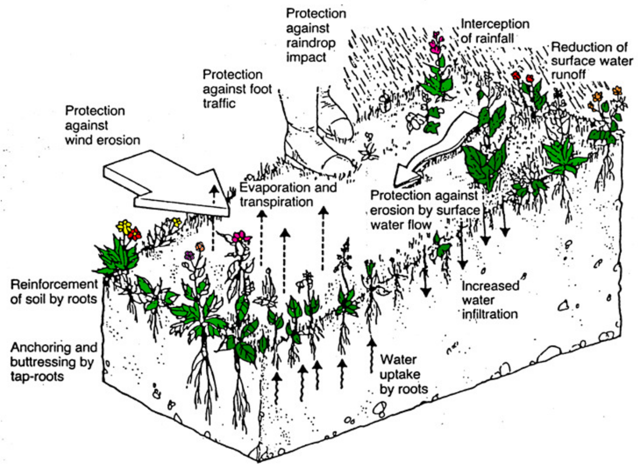


Figure 2 Effect of vegetation on water flow within slope surface (after Coppin and Richards, 1990)

Threats to the environment due to slope failures may affect environmental sustainability. The cost of repairing slopes is more expensive than the cost of preventive measures (Bennett and Doyle, 1997). Therefore, engineers must have a good understanding of the mechanism leading to rainfall-induced slope failures enabling suitable actions to be taken to prevent slopes from failures. This paper explains the role of capillary barrier system, horizontal drains and vegetation in increasing the stability of a residual soil slope during heavy rainfalls through numerical analyses and measurements of matric suction variations in residual soil slopes.

2. HORIZONTAL DRAIN

2.1 Effectiveness of Horizontal Drains

Negative pore-water pressures as a crucial part of the stability of residual soil slopes are needed to be maintained in a slope under varying climatic conditions and considered in the design. Infiltration of rainwater into the slope surface contributes to raising the groundwater table and decreasing negative pore-water pressures. Horizontal drains have been commonly used in stabilization works of unsaturated residual soil slopes. 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), in addition to soil properties and slope geometry as controlling parameters.

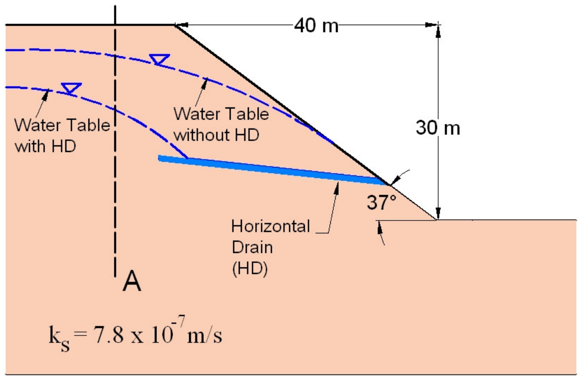
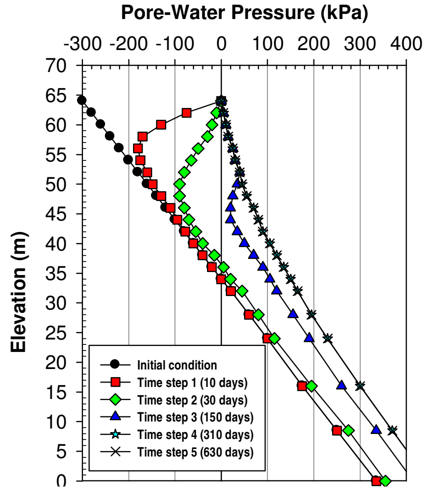
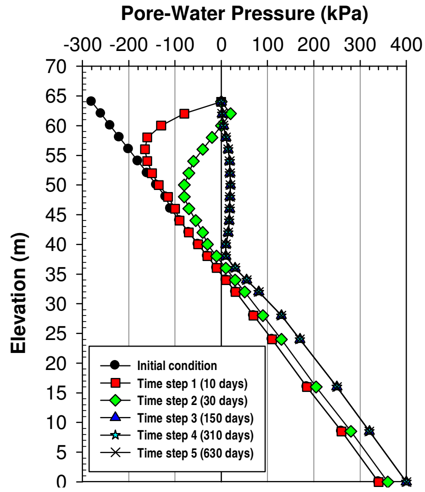


Figure 3 Slope model with and without horizontal drain



(a) Without drains



(b) With drains

Figure 4 Pore-water pressure profiles along section A for slope without drains (a) and with drains (b) (after Rahardjo and Leong, 2002)

Rahardjo and Leong (2002) studied the effectiveness of horizontal drains in typical residual soil slopes under tropical climate. They incorporated the unsaturated soil properties in the parametric study involving various ranges of saturated coefficient of permeability, different shapes of soil-water characteristic curves and permeability functions. The geometry of the slope model used in the parametric study is shown in Figure 3. Figures 4a and 4b show pore-water pressure profiles, obtained from numerical analyses, at section A on the crest of the slope for conditions with and without drains, respectively and for various times during the rainfall application. The parametric study indicated that the horizontal drain is effective in lowering the groundwater table (Figure 3). As a result, the stability of the slope is also improved.

2.2 Location of Horizontal Drains

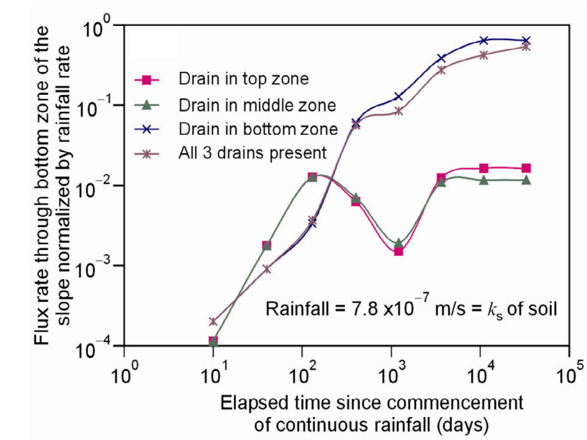
Rahardjo et al. (2003) studied the effective location of horizontal drains in stabilising residual soil slopes against rainfall-induced slope failures under a tropical climate. The study includes field instrumentation at two residual soil slopes complemented with a parametric study relating to drain position. Typical slope geometry and soil properties for residual soil slopes in Singapore were used in the parametric study. A continuous rainfall rate equivalent to k_s was applied to the slope for all five drainage configurations until equilibrium was achieved.

Seepage analyses were carried out using the finite element seepage software Seep/W (Geo-Slope, 1998a) and the results showed that the flux rate through the bottom zone of the slope was relatively the same when either a single drain was present in this bottom zone or if all three drains were present in the slope (Figure 5a). A factor of safety was calculated for each drainage scenario at each time step by importing the pore-water pressure head files from Seep/W into Slope/W model (Geo-slope, 1998b). The results of the slope stability analyses are shown in Figure 5b. The general trend of Figure 5 shows that the most benefit was derived from the drain located at the bottom of the slope.

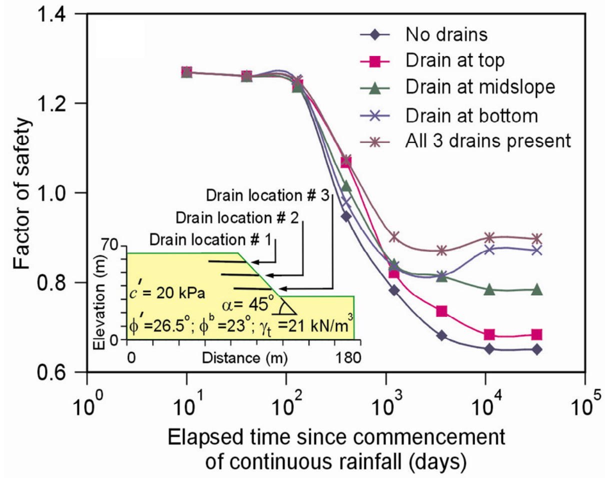
Based on the results of the parametric study, horizontal drains were installed in two residual soil slopes in Singapore and their performance was monitored through field instrumentation (Rahardjo et al., 2003). Field monitoring results also indicate that horizontal drains were found to be most effective when located at the base of a slope (Rahardjo et al., 2003). On the other hand, Rahardjo et al. (2003) observed from field monitoring results that horizontal drains are only effective for lowering groundwater table rather than preventing the development of perched water table. In other words, the region above the already lowered groundwater table and below the zone of influence due to rainfall could potentially be considered as the zone where a constant matric suction profile can be maintained and can provide an additional factor of safety to the slope through the gain in shear strength.

2.3 Length of Horizontal Drains

The length of horizontal drains affects the effectiveness of horizontal drain system. Therefore, Santoso et al. (2009) investigated the effectiveness of different lengths of horizontal drain in residual soil slopes in Singapore. They carried out slope stability analyses before the installation of horizontal drain to obtain the location of the critical slip surface within the investigated slopes. This critical slip surface was used as a reference to determine the length of horizontal drain in the seepage analyses. The length of the horizontal drain was started from the slope surface near the toe until the critical slip surface. The inclination of the horizontal drain was 7o. Seepage analyses were also carried out with the length of horizontal drain extended to the crest of the slope and the middle of the slope (Santoso et al., 2009). Typical soil-water characteristic curve (SWCC) and permeability functions of residual soils in Singapore were used in the seepage analyses of typical slopes under an applied rainfall intensity of 22 mm/hr for 24 hours.



(a) Flux rate



(b) Factor of safety

Figure 5 Theoretical effectiveness of horizontal drains in terms of flux through bottom zone of the slope with respect to different drain positions (a) and factor of safety with respect to different drain positions (b) (modified from Rahardjo et al., 2003)

Figure 6 shows the improvement of slope stability in the residual soil slope of the sedimentary Jurong Formation and the Bukit Timah Granite with the installation of horizontal drains within these slopes. Figure 6 also shows the non-linear relationship between the increasing factor of safety and the ratio of drain length to drain spacing. The factor of safety tends to be constant after the length of horizontal drain reaches the critical slip surface. It explains that the effectiveness of the length of the horizontal drain is limited by the critical slip surface. It is concluded 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 in improving the slope stability should be also considered based on drain spacing, drain diameter, and drain location. In addition, soil properties also influence the effectiveness of horizontal drains in maintaining stability of slopes.

2.4 Field Instrumentations

Horizontal drains were installed within the sedimentary Jurong Formation residual soil slope at Havelock Road. One row of 12 m to 18 m long horizontal drains was installed with a 5° inclination and 3 m lateral spacing. They were located near the toe of the slope. Three rows of tensiometers were installed near the crest, in the middle and near the toe of the slope to monitor the negative pore-water pressures changes during dry and wet periods. Each row consisted of three tensiometers located at depths of 0.5, 1 and 2 m below slope surface. Three Casagrande piezometers were installed near the crest (P1 at 14 m depth), in the middle (P2 at 10 m depth) and near the toe (P3 at 10 m depth) of the slope within the area with horizontal drains to monitor the changes in groundwater table during dry and wet periods.

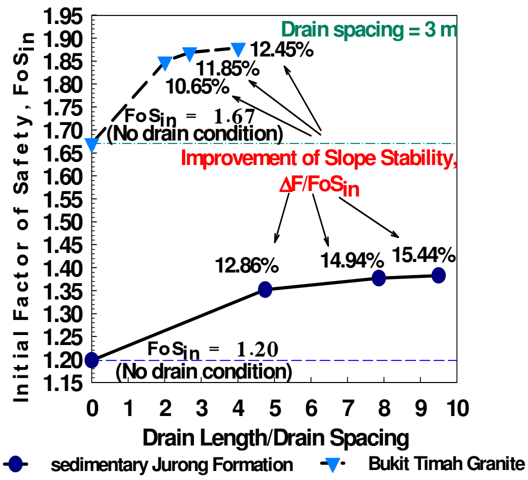


Figure 6 Influence of drain length on stabilizing effect of horizontal drains on sedimentary Jurong Formation and Bukit Timah Granite residual soil slopes (after Santoso et al., 2009)

The monitoring results of piezometer show that the groundwater table decreased significantly after the installation of horizontal drains (Figure 7). Figure 7 shows 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.

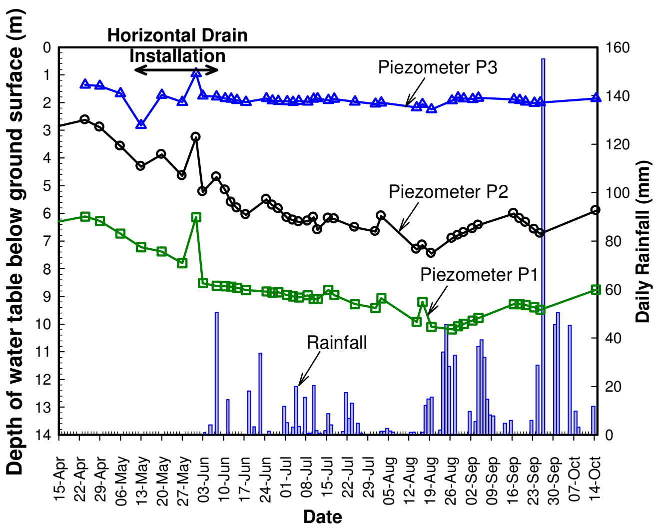
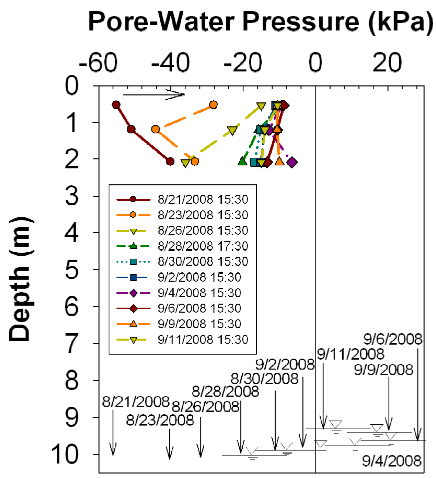
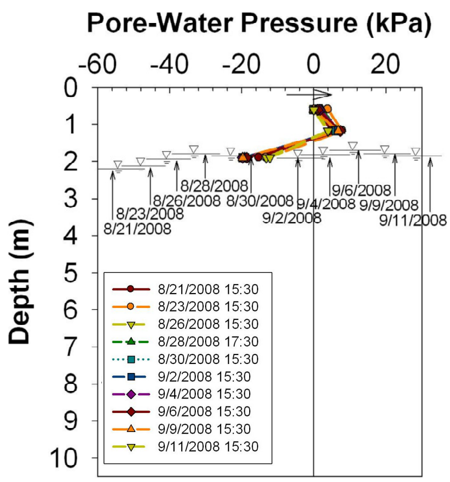


Figure 7 The piezometer reading before and after the installation of horizontal drains within the residual soil slope at Havelock Road

The monitoring results of piezometers near the crest and the toe of the slope at Havelock Road (Figures 8a and 8b) show that the groundwater table did not change during the rainfall period from 21 August to 11 September 2008. However, the negative pore-water pressures near the slope surface change due to the infiltration of the rainwater. Figures 8a and 8b show that the horizontal drains are effective to maintain the location of groundwater table during rainfall. However, horizontal drains cannot be used to maintain the negative pore-water pressure near the slope surface. These results verified the study by Rahardjo and Leong (2002) that the horizontal drains are only effective to improve the stability of the slope by lowering the groundwater table. The field monitoring results at Havelock Road also verified the study by Rahardjo et al. (2003) that the horizontal drains are effective to maintain the location of the groundwater table if they are located near the toe of the slope.



(a) Crest



(b) Toe

Figure 8 Pore-water pressure profiles near the crest (a) and the toe (b) of the Havelock Road slope during rainfall (21 August to 11 September 2008)

Stability analyses of slope at Havelock Road were carried out to study the effect of horizontal drains on slope stability. "Total cohesion" method (Fredlund and Rahardjo, 1993) was used to analyze the stability of the slope. Soil cohesion was calculated using the pore-water pressures measured from 21 August to 11 September 2010 at Havelock Road. The variations of soil cohesion were incorporated in SLOPE/W (Geoslope, 2007) to obtain the varying factor of safety of the slope at Havelock Road during and after rainfall. Figure 9 shows that the factors of safety for slope without horizontal drains are much lower than those of the slope with horizontal drains. It indicates that horizontal drains are effective to maintain the groundwater table position and shear strength of the slope at Havelock Road during rainfall.

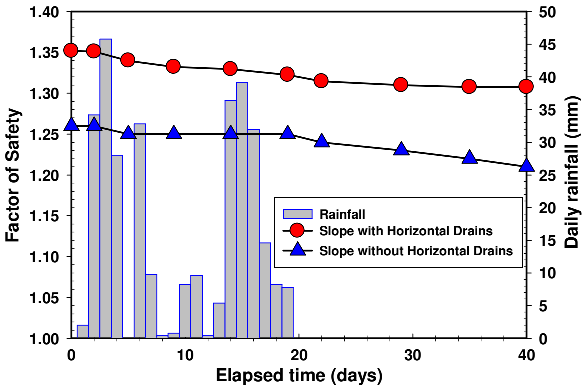


Figure 9 Factor of safety variation of the residual soil slope at Havelock Road from 21 August 2008 until 10 September 2008

3. CAPILLARY BARRIER SYSTEM

3.1 Mechanism of Capillary Barrier System

The principle of capillary barrier system (CBS) is based on the contrast in unsaturated hydraulic properties (soil-water characteristic curves and permeability functions) of each material. Based on unsaturated soil mechanics theory, the coefficient of permeability as well as the water content of the coarse-grained soil can be much lower than that of the fine-grained soil at high suction values (Figure 10).

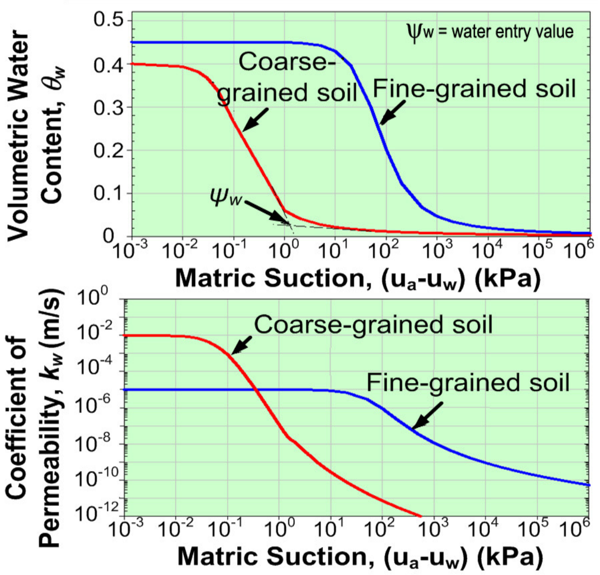


Figure 10 Soil-water characteristic curves and permeability functions of capillary barrier system

Under unsaturated conditions, the difference in permeability between the fine-grained layer and the coarse-grained layer limits the downward movement of water through capillary barrier effect. The infiltrated water is then stored in the fine-grained layer by capillary forces. This infiltrated water is ultimately removed by evaporation and transpiration, lateral drainage through the slope or percolation into the underlying layer. When percolation (breakthrough) takes place, the capillary barrier no longer impedes water from infiltrating into the slope. Figure 11 shows the mechanism of CBS in minimizing the infiltration of rainwater into the slope.

3.2 Materials of Capillary Barrier System

The CBS materials must be selected properly with careful consideration on controlling the parameters with respect to material properties in order to design an effective CBS. Rahardjo et al. (2006) carried out a parametric study to obtain the controlling parameters of the CBS materials. The results showed that there are three controlling parameters that must be considered in selecting the CBS materials, which are: the ratio between the water-entry value of the fine-grained layers and the coarse-grained layers (ψ_w-ratio), water-entry value of the coarse-grained layer and saturated coefficient permeability of the fine-grained layer.

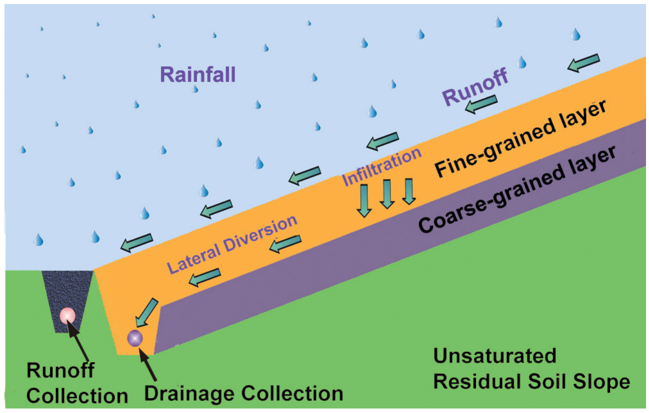


Figure 11 Capillary barrier system

Rahardjo et al. (2006) concluded that the minimum ψ_w-ratio should be 10 to create the barrier effect between the fine-grained layer and the coarse-grained layer and to minimize the infiltration of water into the coarse-grained layer. The coarse-grained layer must have a low water-entry value (preferably less than 1 kPa) in order to maintain the effectiveness of the CBS. The saturated coefficient permeability of the fine-grained layer should not be too low (preferably higher than 10^{-5} m/s) to allow water to flow out from the fine-grained layer by lateral diversion and as a result, the CBS remains effective.

In addition to the three controlling parameters, Tami et al. (2007) concluded that the fines content within fine-grained layers also affect the effectiveness of the CBS. The fine-grained layer should have low fines content so that the SWCC of the soil for the fine-grained layer will be steep and the soil is able to drain a large amount of water during a rainfall. As a result, the storage capacity of the fine-grained layer is increased rapidly after the rain stops. In addition, the use of soils with low fines content as the fine-grained layer prevents the development of cracks in the upper layer of CBS, especially during dry period when matric suctions are high.

3.3 Laboratory experiments of Capillary Barrier System

Several laboratory tests have been carried out to study the water flow through soil layers in CBS. Yang et al. (2004) constructed soil columns to study one-dimensional (1-D) infiltration of water through soil layers in the CBS. The infiltration tests were performed using several combinations of CBS materials, such as fine sand overlying medium sand, medium sand overlying gravelly sand, fine sand overlying gravelly sand and silty sand overlying gravelly sand. It was concluded that a saturated coefficient permeability ratio of 2 to 3 orders of magnitude between the fine-grained and the coarse-grained layers was generally effective to produce a capillary barrier effect. Yang et al. (2004) also suggested that the minimum thickness of the coarse-grained layer required in a CBS is approximately equal to the residual matric suction head of the coarse-grained layer, which is also close to the water-entry value of the coarse-grained layer. A coarse-grained layer which is thicker than the minimum thickness may not affect the barrier effect, while a coarse-grained layer which is thinner than the minimum thickness will reduce the barrier effect.

Tami et al. (2004a) investigated the potential use of CBS as a slope stabilization technique by limiting infiltration into a soil slope. An infiltration box of 2.45 m in length, 2 m in height and 0.4 m in width was used to construct the laboratory capillary barrier model. Three combinations of materials consisting of 0.2 m thick fine sand overlying 0.2 m thick gravelly sand, 0.4 m thick fine sand overlying 0.2 m thick gravelly sand and 0.2 m thick silty sand overlying 0.2 m thick gravelly sand were investigated. The inclination angle of the CBS model was 30°. The experimental results showed that CBS has high potential application as a slope stabilization measure against rainfall-induced slope failures.

Indrawan et al. (2006) investigated the use of soil mixtures as fine-grained layers in CBS. The soil mixtures used as the fine-grained layers were a soil mixture of 50% residual soil and 50% gravelly sand (RG-50), a soil mixture of 75% residual soil and 25% medium sand (RM-75) and a soil mixture of 95% residual soil and 5% lime (RL-95). The experimental results indicated that the RG-50 and RM-75 were more effective than the RL-95 in maintaining matric suctions during wetting process. However, the RL-95 was found to be more effective than the RG-50 and RM-75 in draining water.

Krisdani et al. (2006) conducted a 1-D laboratory test to investigate the infiltration characteristics through a capillary barrier system and the storage of the fine-grained layer. The performance of capillary barrier models constructed using different materials (i.e. geosynthetic material and gravelly sand) as coarse-grained layer was also studied. The experimental results showed that capillary barrier effect existed in both capillary barrier columns with geosynthetic material and gravelly sand as the coarse-grained layer. During the rainfall tests, the geosynthetic material was found to be more effective than the gravelly sand to be used as the coarse-grained layer in a capillary barrier system. Krisdani et al. (2006) concluded that the recovery of water storage of the CBS is mainly controlled by the lateral diversion flow and the evapotranspiration process. The evaporation process alone is not sufficient to remove the infiltrated water in the CBS constructed in the tropical region.

3.4 Field Instrumentations of Capillary Barrier System

Rahardjo et al. (2010) instrumented the Bukit Timah Granite residual soil slope at Ang Mo Kio using tensiometers and piezometers (Figure 12). The slope experienced failure several times and had been repaired using CBS. Manual monitoring of the tensiometers and piezometers was done five times a week (Monday – Friday) at the same time for the first month. Subsequently, manual monitoring was carried out three times a week (Monday, Wednesday and Friday) at the same time. Rainfall data were obtained from the nearest rainfall station which was about 0.9 km away from the site. Manual monitoring of tensiometers and piezometers was conducted for a period of 10 months, starting from February to November 2008.

The monitoring results showed that pore-water pressures in the slope with capillary barrier system were able to maintain negative pore-water pressures (matric suction) under rainfall conditions as illustrated in Figures 13 and 14. As a result, the presence of negative pore-water pressure contributed to the shear strength of the soil, resulting in the slope to be less susceptible to failure. On the other hand, the pore-water pressure under the original slope was easily affected by the rainfall infiltration. Figures 13 and 14 illustrate that the pore-water pressures under the original slope followed the rise and fall of rainwater infiltration. Pore-water pressures under the original slope were unable to maintain negative values when rainfall occurred. In general, during rainfalls, the pore-water pressures in the slope with capillary barrier system were generally lower than the pore-water pressures in the original slope, demonstrating the effectiveness of capillary barrier system in minimizing rainfall infiltration into the slope.

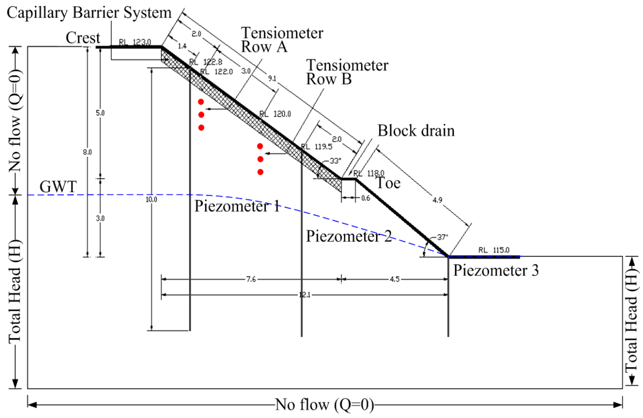


Figure 12 Schematic diagram of capillary barrier system at Ang Mo Kio slope (After Rahardjo et al., 2010)

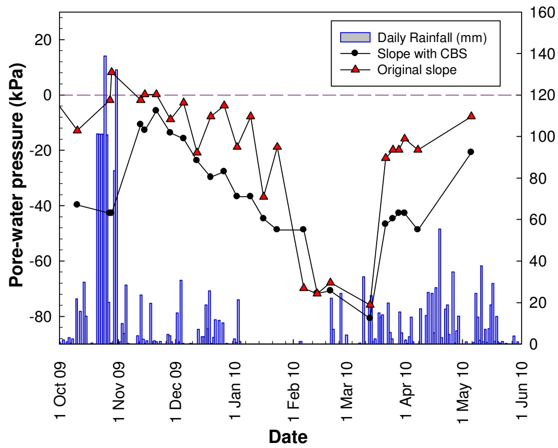


Figure 13 Pore-water pressures variations for original slope and slope with CBS for tensiometer at row A and at 1.15 m depth

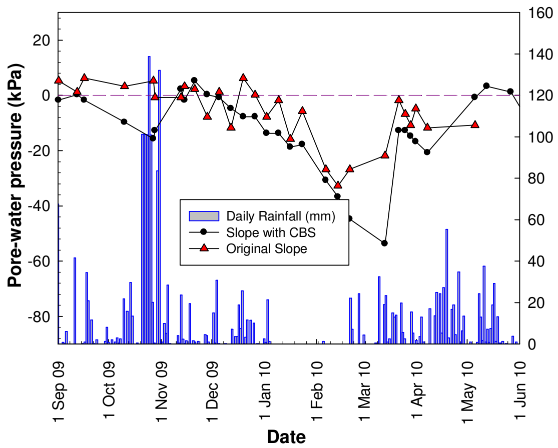


Figure 14 Pore-water pressures variations for original slope and slope with CBS for tensiometer at row B and at 1.15 m depth

CBS was also constructed at a residual soil slope at Tampines. The slope is located at Old Alluvium and quite gentle with only 20° of slope angle. The CBS was constructed using fine sands as the fine-grained layer and recycled concrete aggregates as the coarse-grained layer (Figure 15). Several instruments were installed at CBS slope and original slope at Tampines to investigate the effectiveness of the capillary barrier system in minimizing rainwater infiltration and improving stability of the slope. Four tensiometers at different depths (0.6 m, 1.2 m, 1.5 m and 2 m) were installed in the middle of the CBS slope. The original slope next to CBS slope was also instrumented using tensiometers installed at the same depths with those at CBS slope. Three piezometers were installed near the crest, in the middle and near the toe of the orginal slope to observe the variation of groundwater table location during dry and wet periods. Rainfall gauge was installed at the crest of the original slope to obtain the rainfall data. All instruments were connected to data acquisition system to monitor the instruments' readings continuously during dry and wet periods.

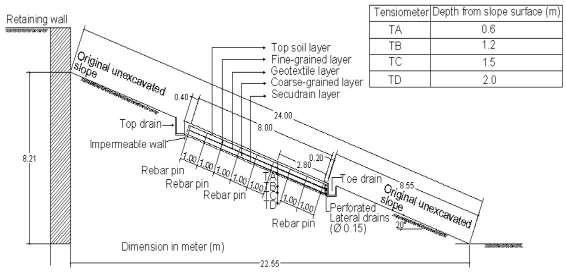
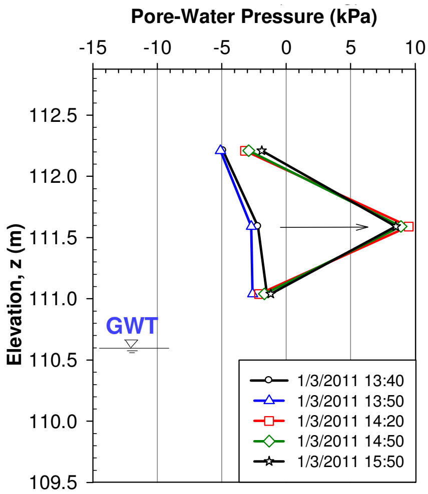
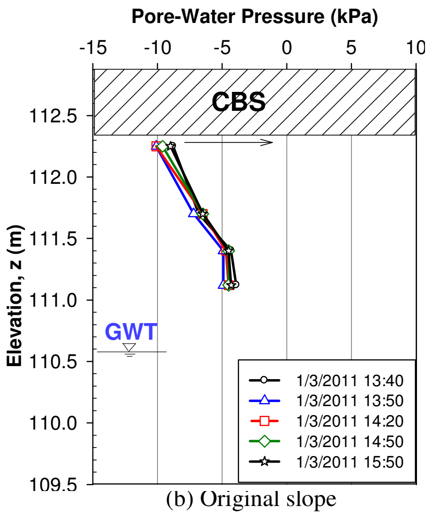


Figure 15 Schematic diagram of capillary barrier system at Tampines slope



(a) CBS slope



(b) Original slope

Figure 16 Pore-water pressure profiles for the CBS slope (a) and the original slope (b) during rainfall at Tampines on 3 January 2011

The monitoring results of tensiometers showed that the negative pore-water pressures during rainfall were relatively constant at the CBS slope as compared with those in the original slope (Figure 16). In addition, the negative pore-water pressures in the CBS slope were higher than those in the original slope. It showed that CBS was effective to minimize the infiltration of rain water into deeper layers of the slope at Tampines. The monitoring results also showed that the recycled concrete aggregates can be used to replace gravel as a coarse-grained layer in CBS.

Stability analyses of slope with CBS and original slope at Tampines were carried out using the "total cohesion" method. Soil cohesions were calculated using pore-water pressure measurements on 3 January 2011 at Tampines slope. The variations of soil cohesion were incorporated into the slope stability analyses to obtain the variations of factor of safety during and after rainfall on 3 January 2011. Figure 17 shows that the factor of safety of slope with CBS at Tampines was relatively constant during and after rainfall on 3 January 2011. On the other hand, the factor of safety of original slope at Tampines decreased significantly (Figure 17) during rainfall showing the effectiveness of CBS in minimizing rainwater into slope.

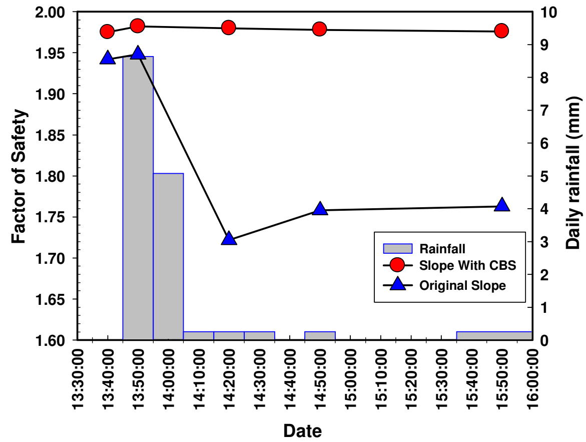


Figure 17 Factor of safety variation of the residual soil slope at Tampines on 3 January 2011

4. EFFECT OF VEGETATION ON SLOPE STABILITY

4.1 Mechanism of vegetation as slope cover

Vegetation effect on slope stability may be broadly classified as either hydrological or mechanical in nature. The mechanical factors arise from the physical interactions of either the foliage or root system of the plant with the slope. The hydrological mechanisms are those intricacies of the hydrological cycle that exist when vegetation is present (Greenway, 1987). Wu et al. (1979) concluded that the shear strength contributed by tree roots is important to the stability of slopes.

Contribution of the root reinforcement to the soil can be considered as an additional term in the shear strength of the soil (S):

$$S = C + (\sigma - u_a)\tan\phi' \qquad (1)$$

where:

$$C = c' + (u_a - u_w)\tan\phi^b + c_r \qquad (2)$$

$$c_r = T_r\left(\frac{A_r}{A}\right)(\sin\theta + \cos\theta\tan\phi') \qquad (3)$$

C = total cohesion (kPa); c'= effective cohesion of soil (kPa); u_a = pore-air pressure (kPa); u_w = pore-water pressure (kPa); ϕ_b = angle indicating the rate of change in shear strength relative to changes in matric suction (ua-uw), ϕ' = effective friction angle of soil (degrees); c_r = cohesion due to roots (kPa); T_r = tensile strength of roots (kPa); A_r/A = area of shear surface occupied by roots, per unit area (root-area ratio); θ = shear deformation from vertical (degrees).

Parametric studies were carried out to study the effect of vegetation on the stability of slope. A slope with 15 m height and 30° slope angle was used as a typical slope. Typical soil properties for residual soil slope in Singapore were used in the stability analyses, such as unit weight of 20 kN/m^3, effective friction angle of 26° and effective cohesion of 10 kPa. Two categories were considered in the parametric studies. The first category assumed ϕ^b angle was equal to zero or no contribution from matric suction and c_r varied from 0 to 15 kPa. The second category assumed no contribution from vegetation (c_r = 0), ϕ^b = 11° and matric suction varied from 0 to 75 kPa. The parametric studies using the first category were carried out to study the effect of vegetation with 1 m depth of root on the stability of slope. Those two categories were included in the parametric studies in order to compare the effect of matric suction with the effect of vegetation on the improvement of the stability of the slope. The results of parametric studies (Figure 18) show that the vegetation can be used to improve the stability of the slope. However, the contribution of root is not as significant as the contribution from matric suction in improving the stability of the slope.

4.2 Type of vegetation for slope cover

The selection of vegetation for slope cover depends on hydro-geological condition of the slope, such as: rainfall intensity, soil properties, temperature, and evaporation rate. Common vegetations used as slope cover are Vetiver and Orange Jasmine.

Vetiver, is a perennial grass of the Poaceae family, native to India (Dalton et al., 1996). Vetiver is a fast growing grass which can grow up to 3 meters high in 12 months (Dalton et al., 1996). Unlike most grasses, which form horizontally spreading mat-like root systems, Vetiver's roots grow downward, 2–4 meters in depth. Vetiver is widely cultivated in the tropical regions of the world.

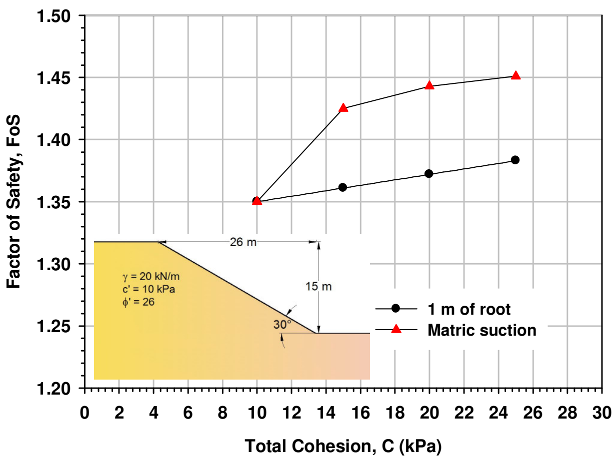


Figure 18 The effect of vegetation on the stability of slope

A review conducted by the US Board of Science and Technology for International Development (National Research Council, 1993) showed that the Vetiver grass system has been successfully used as an effective and simple means for many applications such as slope stabilization in tropical and subtropical regions of the world. It has been used since 1900's in West Indies South Africa (National Research Council, 1993), Brazil (Grimshaw, 1994) and Fiji (Truong and Gawander, 1996). It was also grown at Serdang (near Kuala Lumpur), Malaysia (World Bank, 1995).

Orange Jasmine, is a small tropical, evergreen plant bearing small, white, scented flowers, and is grown as an ornamental tree or hedge (Llamas, 2003). It can grow up to 7 m tall. The plant flowers throughout the year. The fruit of Murraya paniculata is coloured red to orange, and grows up to 1 inch in length. It is a local shrub to tropical regions of the world including Singapore.

4.3 Field Instrumentations

Vetiver grass and Orange Jasmine shrub were planted on a soil slope in the Old Alluvium formation. The grass and the shrub were planted within 0.2 m thick of top soil next to each other. The slopes were then instrumented with tensiometers at several depths (0.3, 0.6 and 1.2 m) to measure the negative pore-water pressure in the soil. One row of tensiometer was installed in the slope with grass and in the slope with shrub. In addition, another row of tensiometer was installed in the original slope adjacent to the slope with grass to investigate the effect of grass and shrub on slope stability. The layout of the instrumentation is presented in Figure 19.

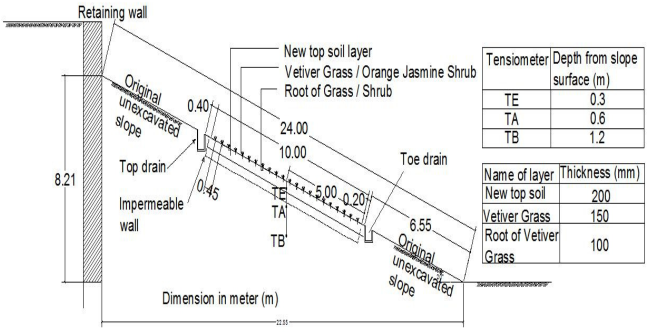
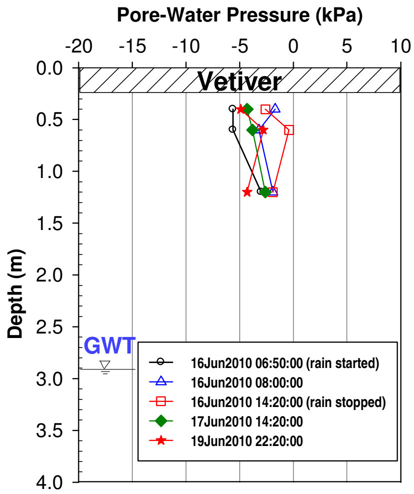


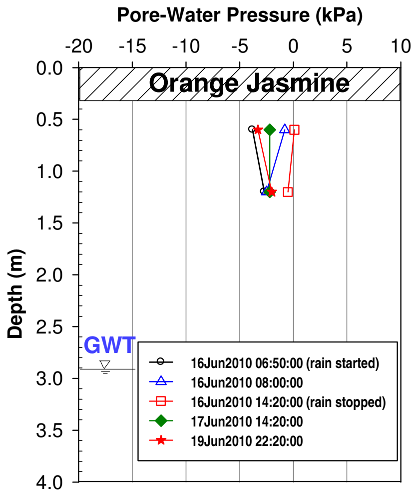
Figure 19 Typical cross section of slope covered with Vetiver grass and Orange Jasmine shrub

The pore-water pressures measured by the tensiometers were recorded automatically using a data acquisition system. Figure 20 shows the pore-water pressure profiles measured by tensiometers in the slope with grass and the slope with shrub, respectively. It can be seen that the pore-water pressures remained negative in both slopes during rainy and dry periods. The monitoring results from original slope show that pore-water pressure increased significantly due to rainfall (Figure 21) and it decreased again during dry period. The monitoring results show that Vetiver grass and Orange Jasmine shrub are effective in minimizing infiltration into greater depths. As a result, the pore-water pressure is maintained at negative values during rainy period and consequently, it can prevent rainfall-induced slope failures.

Stability analyses of the orginal slope and the slopes covered with Vetiver and Orange Jasmine at Tampines were carried out using the "total cohesion" method. The pore-water pressures measured from 16 June 2010 until 17 June 2010 were used to calculate soil cohesions during and after rainfall at Tampines slope. The variations of soil cohesion were incorporated into slope stability analyses to obtain the variations in factor of safety during and after rainfall from 16 June 2010 until 17 June 2010 at Tampines slope. Figure 22 shows that the factor of safety at the original slope decreased significantly during rainfall on 16 June 2010. On the other hand, the factors of safety of the slopes covered with Vetiver and Orange Jasmine were relatively constant during rainfall on 16 June 2010, indicating the effectiveness of vegetation (Vetiver and Orange Jasmine) in minimizing rainwater infiltration into the slope. As a result, the shear strength of the slope was maintained during rainfall.



(a) Vetiver grass



(b) Orange Jasmine shrub

Figure 20 Pore-water pressure profiles at slope with (a) Vetiver grass and (b) Orange Jasmine shrub

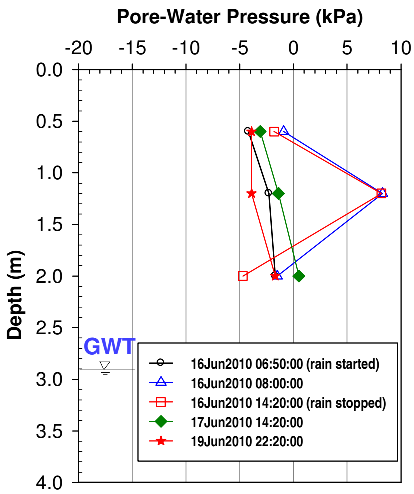


Figure 21 Pore-water pressure profiles at original slope

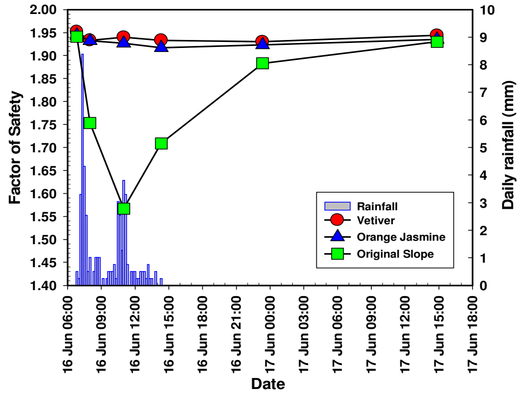


Figure 22 Factor of safety variation of Tampines slope with and without vegetative cover from 16 June 2010 until 17 June 2010

5. CONCLUSIONS

Unsaturated soil mechanics is required to understand the mechanism of rainfall-induced slope failures. The pore-water pressure changes and factor of safety variation of the slope during rainfall can be assessed appropriately using the unsaturated soil mechanics principles. Rainfall was incorporated into seepage analyses in terms of flux boundary applied to the surface of the slope. Soil-water characteristic curve and permeability function were the main parameters for seepage analyses.

Horizontal drains and capillary barrier system can be used as preventive and remedial measures for slopes in Singapore. Horizontal drains function effectively in lowering the groundwater table if they are placed near the bottom of the slope.

Capillary barrier system uses unsaturated soil mechanics for minimizing infiltration into slopes and preventing slope failures. If a slope fails due to rainfall and its groundwater table is high, capillary barrier system can be used as slope repair together with the installation of horizontal drains.

The field monitoring results show that Vetiver grass and Orange Jasmine shrub can be used as slope cover to minimize infiltration of rain water into slope. Both Vetiver and Orange Jasmine are able to maintain negative pore-water pressure during rainfall. The contribution of vegetation on the stability of slope comes from tensile strength of the root and interaction between root and its surrounding soil.

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