Unsaturated soil mechanics for sustainable urban development

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ABSTRACT

The effects of climate change are major concerns for many tropical urban areas, like Singapore. Singapore is mainly covered by residual soils with a significant thickness of unsaturated zone above the groundwater table. In practice, geotechnical engineers commonly ignore the unsaturated soil mechanics in their design to avoid the complexity of analyses. However, the ignorance of the unsaturated soil mechanics can lead to the over conservative designs that may not be sustainable. In most geotechnical designs, such as slope stability, tree stability and deep excavation, the actual flux boundary conditions will be an important concern. Flux boundary conditions (i.e. infiltration, evaporation, transpiration) produce an unsteady-state saturated/ unsaturated flow situation which results in a change in the pore-water pressure and shear strength of soil. Therefore, the effect of climate change, which is translated into flux boundary conditions, should be considered not only in geotechnical design, but also in the assessment of natural structures like slopes and tree stability using the unsaturated soil mechanics principles. This paper presents the application of unsaturated soil mechanics for sustainable urban development. Slope and tree failures may damage surrounding buildings, infrastructure, vehicles as well as cause injuries or fatalities. Therefore, sustainable preventive measures for slope protection against rainfall and for maintaining tree stability are required. As a case study, this paper describes the development of slope susceptibility map with the incorporation of unsaturated soil properties in Singapore. The preventive measure for slopes that fall under the categories of slopes with low factor of safety should be provided. In this paper, the use of capillary barrier system and geobarrier system, that incorporates unsaturated soil mechanics principles and recycled materials, for slope preventive measures against rainfall is presented. In addition, the use of soil mixtures for maintaining tree stability with the unsaturated soil mechanics consideration is also illustrated in this paper. In general, the studies presented in this paper illustrate the successful application of unsaturated soil mechanics principles in slope and tree stability with the main consideration of sustainable developments in urban areas.

Keywords: unsaturated soil mechanics; recycled materials; slope stability; tree stability; sustainable urban development

1 BACKGROUND

Numerous scientific evidences have given credence to the presence of negative impacts from climate change. Climate change has been a major concern for people around the world as it affects their livelihoods and living environments to a considerable extent. A consensus has developed among governments, industries and academics that global warming exists. Due to its urgency and wide-ranging effects, many research works have been conducted to study climate change and the ways to mitigate its impacts. One aspect of climate change is the variations in rainfall patterns, which affect the flux boundary conditions across ground surface. Temperatures are predicted to rise and rainfalls are projected to be more intense and less frequent (Strauch et al., 2014).

A study by Strauch et al. (2014) showed that climate change resulted in the changes in rainfall patterns which may become less frequent, but more intense. Based on a study in Hawaii, he suggested that a decrease in mean annual rainfall is correlated with the increase in rainfall intensity and increased number of dry days with no rainfall. Changes in rainfall patterns, in particular, will influence the flux boundary condition across ground surface. The changes in groundwater hydrology could reduce the shear strength of soil that may result in rainfall-induced slope failures (Ng and Shi, 1998; Cho and Lee, 2002; Chen et al., 2004; Tsai and Yang, 2006; Rahardjo et al., 2013a; Tohari et al. 2007; Xue and Gavin, 2008; Muntohar and Liao, 2009). This could be catastrophic and may claim many lives.

Many studies have been conducted to investigate this complex relationship between slope stability and changes in rainfall patterns around the world. For instance, in the region of Umbria, Italy, it was found that during the warm-dry season, the occurrence of slope failures is relatively unchanged, while during the cold-wet season, landslide events increased considerably when there is an increase in rainfall amount and rainfall intensity (Ciabatta et al., 2016). Furthermore, in Taiwan, where 75% of its area is mountainous, it is predicted that the average temperature would increase by 2 to 3 oC by 2100 as compared to the temperature in 2000, and the seasonal mean precipitation would increase by 2% to 26% (Lin et al., 2014). As a result, the government has identified central Taiwan to be a landslide-prone area and measures have been taken to address the problem.

Due to the complex inter-dependent relationship between water and soil with respect to stability, many studies have attempted to understand this essential relationship, which would allow for more reliable predictions of potential slope hazards. Junqueira Junior et al. (2017), for instance, has investigated the variations of soil water content in a tropical native forest of Brazil, in response to variations in precipitation, and proposed a method for strategic monitoring locations for Soil-water characteristic curves (SWCC) to obtain a representative sample for the particular site. Moreover, soil thickness and rock fragment cover have also been identified by Fu et al. (2011) as key contributing factors to the soil's hydrological and erosional behaviour, in which thicker soils were found to exhibit higher infiltration capacity across various rainfall events.

In Singapore, many studies have been performed on the effects of rainfall on stability of local slopes (Rahardjo et al., 2008a; Rahimi et al., 2010; Kristo et al., 2017). In December 2006 and January 2007, which coincided with the above average monthly rainfall events historically, eleven landslides occurred in Singapore (Rahardjo et al., 2007). Rahimi et al. (2011) have shown that antecedent rainfall affects the stability of low-conductivity (LC) slopes more than high-conductivity (HC) slopes. It was found that different rainfall patterns affect different types of slopes. HC slopes tend to reach its minimum factor of safety (FS) under a delayed rainfall pattern, where the intensity increases with time reaching a maximum value near the end of the rainfall event. In contrast, LC slopes achieved a minimum FS under an advanced rainfall pattern, where the intensity is high at the beginning of the rainfall event and decreases with time.

The groundwater table in residual soil slopes is often deep, located at depths of 5 m to 10 m below the slope surface (Blight and Leong, 2012; Rahardjo et al., 2010) and it is subjected to fluctuation from climatic effects (Wesley, 2010). The contribution of negative pore-water pressure or matric suction above the groundwater table, in the unsaturated soil zone, is significant to slope stability (Fredlund and Rahardjo, 1993). The rainwater infiltration results in the changes in pore-water pressure and water content with depth. In other words, the water content increases and the matric suction decreases. As a result, the soil shear strength decreases and it may trigger slope failures (Fredlund et al., 2012). The effects of unsaturated soils should therefore be considered in slope stability analyses for geotechnical designs (Rahardjo et al., 2012; Alonso et al., 2003; Ng et al., 2001).

Rahardjo et al. (2019) plotted the historical slope failures in Singapore with respect to the distribution of maximum daily of rainfall between 1982 and 2017 (Figure 1). They observed that the locations of historical slope failures did not coincide with the locations of maximum daily rainfall in Singapore. Therefore, the slope stability is not only affected by rainfall, but also depends on the soil properties especially unsaturated soil properties since the zone that is affected by rainfall is the unsaturated zone above the groundwater table.

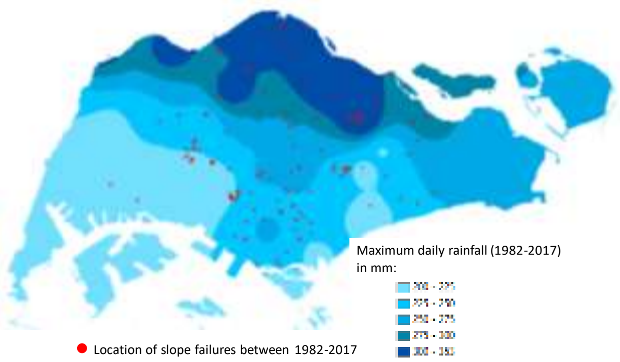

Figure 1. Locations of historical slope failures superimposed with the map of maximum daily rainfall between 1982 – 2017 in Singapore

In Singapore, about 2 million ton of wastes from construction and demolition are generated (BCA-SIA, 2008). For sustainable development, recycling and reuse of these wastes are important. Several waste materials that can be recycled and used are concrete aggregate, asphalt shingle, steel slag and copper slag since these waste materials comprise the largest amounts of waste materials. Concrete aggregate is mainly generated from demolition of building whereas asphalt shingle is a product from transportation works. On the other hand, steel slag is produced from the conversion of iron to steel in an electric furnace while copper slag is a waste material resulted from the process of removing rust and marine deposit in ships. Previous study by Rahardjo et al. (2013b) indicated that recycled concrete aggregates can also be used to replace sand as the material for the fine-grained layer within a capillary barrier system. In Singapore, this recycled concrete is known as recycled concrete aggregates (RCA) (BCA-SIA, 2008). Asphalt shingle wastes are commonly used for sub-base materials for construction of new roads and slope stabilization (Consoli et al., 2002). In Singapore, this recycled waste is known as reclaimed asphalt pavement (RAP). Waste copper slag is commonly used as partial substitute for sand in the production of concrete for structural and non-structural works as reported by Wu et al. (2009). In Singapore, waste copper slag (CS) is allowed to replace sand in concrete (BCA-SIA, 2008). Steel slag (SS) is commonly used as an aggregate in base material for pavement and low-volume roads (Juckes, 2003).

In view of the effects of climate change, greater amounts of rainfall are expected in the future and thus there is a need to prevent future rainfall-induced slope failures. A slope susceptibility map is one common method that can be used to identify areas that are susceptible to slope failures. This paper presents the procedures and methodology for development of slope susceptibility map in Singapore. Appropriate slope preventive measures incorporating unsaturated soil mechanics and recycled materials are proposed to ensure the sustainability of urban area development in Singapore by maintaining the stability of residual soil slopes within susceptible areas during high intensity of rainfall, particularly due to climate change. In addition, trees are an important component of the urban environment and provide numerous advantages to humans. Therefore, this paper also presents the study on finding suitable soil mixtures with unsaturated soil mechanics consideration for maintaining tree stability against wind and rainfall loadings.

2 SATURATED AND UNSATURATED SOIL PROPERTY MAPPING FOR SLOPE SUSCEPTIBILITY

Singapore is located in a tropical region where heavy rainfalls and high temperatures provide conditions for rapid and intense chemical and mechanical weathering that are likely to give rise to deep residual soil profiles (Pitts, 1984). In tropical regions, residual soils frequently exist in unsaturated condition and shallow landslides often occur due to heavy rainfalls. The previous research collaboration projects between NTU and several government agencies have demonstrated that slope failures can be attributed to several factors such as climatic conditions, geological features, topography, vegetation or a combination of these factors. These factors and their contribution to slope instability vary with the geographical location. During the period of 1995 to 2000, NTU and Public Works Department (PWD) joined in a research collaboration, funded by National Science and Technology Board (NSTB) to develop guidelines for stability assessments against rainfall-induced slope failures (Rahardjo et al., 2000). The mechanism that leads to rainfall-induced slope failures in residual soil, the procedures and the necessary equipment for soil characterization in Singapore, especially unsaturated soil properties have been developed throughout the project. Comprehensive instrumentations were set up on those slopes to observe the pore-water pressure variations during dry and wet periods. The results of field observations and numerical analyses were combined to produce useful relationship for conducting preliminary assessments for residual soil slopes in Singapore.

During the period of 2006 to 2010, NTU collaborated with Housing and Development Board (HDB) to study the relationships between soil types and soil properties with the potential of slope failures in Singapore, establish the correlation between local climatic conditions (rainfall, infiltration and evaporation) and slope failures in terms of soil response such as pore-water pressure changes and deformation (Rahardjo et al., 2014). In addition, stability of several selected slopes under typical rainfall and evaporation conditions of Singapore was evaluated and guidelines for preventive and improvement measures for slope instability due to rainfall were established. The study included laboratory tests, numerical analyses and comprehensive instrumentation. Thirty-three (33) critical slopes in Singapore were investigated in this project. The results showed that the stability of slope in Singapore depends on local climatic data and soil properties of each slope, particularly unsaturated soil properties.

As studied by Rahardjo et al. (2000, 2014), rainfall-induced slope failure is one of the potential natural hazards in Singapore's urban terrain. Stability of a slope as quantified by factor of safety is not constant over time but varies in accordance with the variation in flux boundary conditions. In other words, slopes are infrastructures whose stability is highly dependent on environment and whose failure has detrimental impacts on environment and public safety. Therefore, proper assessment and management of residual soil slopes are imperative especially in anticipation of global climatic changes.

Digital soil mapping has become a common tool that is used in the study of soil science owing to the advancement of technology. Compared to the traditional soil survey methods, digital soil mapping is relatively less tedious, less costly and faster in generating the distribution of soil properties (Grunwald, 2010). Slope susceptibility mapping has become a common research topic as it could help researchers, engineers or town planners to predict the possibility of slope failure and come up with mitigation measures against potential slope failures (Shahabi and Hasim, 2015; Erener et al., 2016; Basharat et al., 2016).

Understanding the unsaturated soil behaviour is essential in designing numerous engineering works, such as soil excavation, residual soil slopes analyses and soil compaction (Fredlund et al., 2012). Unsaturated soil mechanics is particularly of importance in analysing rainfall-induced slope failures. Therefore, it is very important to incorporate the spatial distribution of unsaturated soil properties in the development of slope susceptibility map.

Geostatistical analyses provide methods for processing data in digital soil mapping. The core elements of geostatistical analyses are the interpolation methods. One commonly used method is Kriging which is an interpolation method based on the distance-weighting and semivariogram function approach to find the unknown data between measured/known locations. Li and Heap (2011) observed that Ordinary Kriging is the most popular Kriging method. It is the simplest form of Kriging (e.g., no trend, no stratification etc.) since it requires only a single variable (univariate method). In addition, this type of Kriging is also the most robust among all types of Kriging. In this study, Ordinary Kriging was used in the development of geospatial distribution of the saturated and unsaturated properties of the residual soil from Bukit Timah Granite. The geostatistical analyses were carried out using ArcGIS software (McCoy and Johnston, 2002).

The Kriging analyses require basic map of Singapore and the soil properties data from 80 boreholes within residual soils in Singapore. All boreholes data contain saturated shear strength data (i.e. effective cohesion, c' and effective friction angle, ϕ') whereas only 40 boreholes data have saturated permeability (ks) and unsaturated soil properties data, such as: variables of SWCC (i.e. air-entry value, AEV) and the angle indicating the change in shear strength due to the change in matric suction (ϕb angle). The locations of the investigated boreholes used in this study are presented in Figure 2.

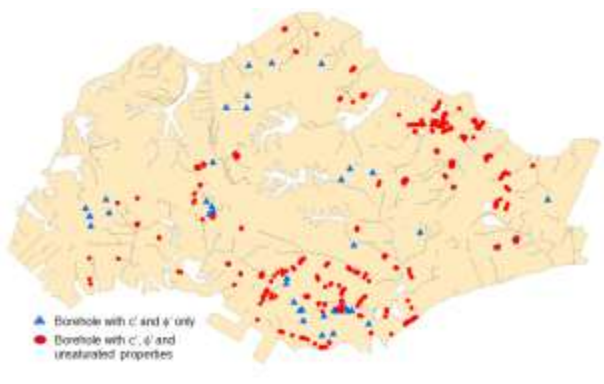

Figure 2. Locations of boreholes with c', ϕ' and unsaturated soil properties

In this study, the slope susceptibility map was developed by conducting 1-D based seepage analysis and infinite slope-based stability analysis using Transient Rainfall Infiltration and Grid-based Regional Slope Stability (TRIGRS) code (Baum, 2008). The TRIGRS implemented the unsaturated soil mechanics principles for analyses of the unsaturated zone above the groundwater table. For the unsaturated zone, the code solves the 1-D Richard's equation that expresses the rate of change of volumetric water content within a soil depth due to water flow through the unsaturated zone. The water table rise is observed with the accumulation of the infiltrated water at the base of the unsaturated zone (Baum et al., 2008). An analytical solution to a pressure diffusion equation based on Iverson (2000) is used to model the pore-water pressure increase at the basal boundary between saturated and unsaturated zones. The model adopts the soil-water characteristic curves (SWCC) and unsaturated permeability proposed by Gardner (1958) for the unsaturated zone (Equations 1 and 2). TRIGRS uses a simple method for routing of surface run-off from cells that have excess surface water, which is done instantaneously and does not take into account the time-lag associated with open-channel flow dynamics. TRIGRS can take into account the spatial heterogeneity of the in-situ soil properties, allowing the user to consider different values of soil characteristics in each cell.

$$k_w = k_S \exp(\alpha\psi^*) \tag{1}$$

$$\theta_w = \theta_r + \left(\theta_s - \theta_r\right) \exp(\alpha\psi^*) \tag{2}$$

where k_w is the hydraulic conductivity function, k_s is the saturated hydraulic conductivity, α is a fitting parameter, ψ^* is pore-water pressure head, θ_w is the volumetric water content, θ_r is the residual water content, and θ_s is the saturated water content.

The spatial distributions of soil properties from 680 boreholes were estimated using ordinary kriging analyses. The spatial distributions of air-entry value and saturated permeability are presented in Figures 3 and 4, respectively. The estimated air-entry value, saturated water content, residual water content from kriging analyses were used to develop SWCC graph based on Fredlund and Xing (1993) equation. Then, Gardner (1958) equation was used to best fit this graph. The associated fitting parameter, α, from Gardner (1958) was used in TRIGRS analyses. The hydraulic diffusivity (D) of the soil was calculated using equation 3.

$$D = \frac{\alpha k_S}{\theta_s - \theta_r} \tag{3}$$

The maximum depth used to calculate factor of safety in the analysis was assumed to be 6.5 m since typical critical slip surface for residual soil slopes in Singapore is located at a depth less than 6.5 m. Based on the Code of Practice of Power and Utilities Board, Singapore (PUB, 2013) for drainage system design, the maximum total amount of rainfall in a day is 533.2 mm. Therefore, a rainfall loading of 22 mm/h for 24 hours (or total rainfall of 528 mm per day) was used in the analysis. The transient analysis in TRIGRS was carried out based on Iverson (2000) model which requires only three parameters to predict the magnitude and timing of the transient pore-water pressure, that are rainfall intensity, duration, and soil hydraulic diffusivity. Some limitations of this approach are the assumption that the soil was homogeneous for one particular zone, the direction of water was assumed isotropic in the analysis, the rainwater infiltration was calculated based on 1-D infiltration model and the stability analysis was carried out based on an infinite slope model. However, these assumptions produced the worst scenario of the factor of safety variations. Hence, the slope susceptibility map could generate a more conservative susceptibility map. In addition, the unsaturated shear strength was incorporated in an infinite slope model to take into account the effect of negative pore-water pressure or suction above the ground water table on the factor of safety calculation. The extended Mohr-Coulomb envelope for the unsaturated shear strength is shown in Figure 5. The spatial distributions of c', ϕ' and ϕ^b angles are illustrated in Figures 6, 7 and 8, respectively.

Figure 3. Spatial distribution of air-entry value

Figure 4. Spatial distribution of saturated permeability

In addition to soil parameters, TRIGRS also requires the spatial distribution of slope angle and elevation as input for stability analyses of the residual soil slopes in Singapore. These two layers were extracted from Digital Elevation Model (DEM) of Singapore (Figure 9). The 1-D infiltration analyses to obtain changes in groundwater table and the subsequent identifications of the critical depth with respect to the lowest factor of safety were carried out at each 1-m pixel of the elevation and slope angle layers. The variations in factor of safety at all pixels were imported into ArcGIS to obtain a spatial distribution of factor of safety.

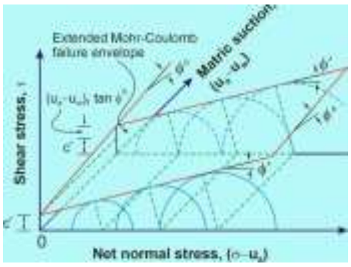

Figure 5. Extended Mohr-Coulomb envelope for shear strength of the unsaturated soil (modified from Fredlund and Rahardjo, 1993)

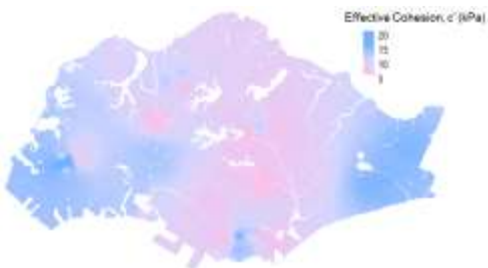

Figure 6. Spatial distribution of effective cohesion

Figure 7. Spatial distribution of effective friction angle

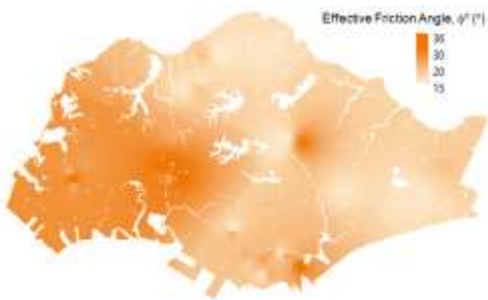

Figure 8. Spatial distribution of ϕ^b value

Figure 9. Digital elevation model of Singapore

Figure 10 presents the slope susceptibility map generated using 1-D infiltration and slope stability analysis incorporating saturated and unsaturated soil properties. The slope susceptibility map illustrates the variations of factor of safety. The minimum allowable factor of safety for slopes in Singapore is 1.5 (HDB, 2012; LTA, 2010). Therefore, the map is divided into two classifications, the slopes with factor of safety (FOS) equal or less than 1.5 and the slopes with FOS higher than 1.5. In Figure 15 the grey color region have a factor of safety greater than 1.5. In contrast, the pixels with black colour have a factor of safety equal or less than 1.5, indicating the slopes which are prone to failure and require preventive measures or slope monitoring. The failures of these slopes may endanger the surrounding houses or buildings. In this case, the slope susceptibility map will benefit engineers in managing the slopes within the urban area especially those critical slopes with a factor of safety lower than 1.5.

Figure 10. Generated slope susceptibility map of Singapore

Parametric studies were carried out on slopes within Nanyang Technological University (NTU) zone as indicated in Figure 10. The studies were conducted to assess the role of the unsaturated soil properties in the development of slope susceptibility map. Figure 11 shows the slope susceptibility map established with the assumption that the slope was fully saturated while Figure 12 presents the slope susceptibility map developed with the incorporation of the unsaturated soil properties (i.e. SWCC, the unsaturated permeability and the unsaturated shear strength). In Figure 11, the areas with slopes having FOS of less than 1.5 are quite extensive when the saturated soil properties were used for the development of slope susceptibility map, resulting in unreasonably high costs being required for slope preventive measures and/or slope repairs. However, upon close inspection, slopes located within the area with FOS of less than 1.5 appear to be stable without any protection. In other words, those slopes are actually unsaturated soil slopes where matric suctions contribute to the shear strength and stability of the slopes. As a result, the FOS of these slopes are actually higher than 1.5 and can be considered safe and do not require any slope improvement work. In summary, the generated slope susceptibility map with the assumption of fully saturated slope was unreasonable and unsustainable for urban area development.

On the other hand, the areas with slopes having FOS of less than 1.5 are not so extensive in the slope stability map with the incorporation of the unsaturated soil properties as depicted in Figure 12. Furthermore, upon close inspection of the slopes with FOS of less than 1.5, it appears that these slopes indeed have a marginal FOS of less than 1.5 since they are currently supported by a retaining wall. In other words, the slope susceptibility map with the incorporation of the unsaturated soil properties is more realistic since the marginal FOS agrees with the slope condition in the field. The more realistic slope susceptibility map will prevent unnecessary cost of overdesigned slopes through the unnecessary slope improvement works and monitoring that are not sustainable for urban area development. These parametric studies illustrate that the unsaturated soil properties play an important role in the development of realistic and sustainable slope susceptibility map.

Figure 11. Generated slope susceptibility map within NTU zone with the assumption of **fully saturated slope**

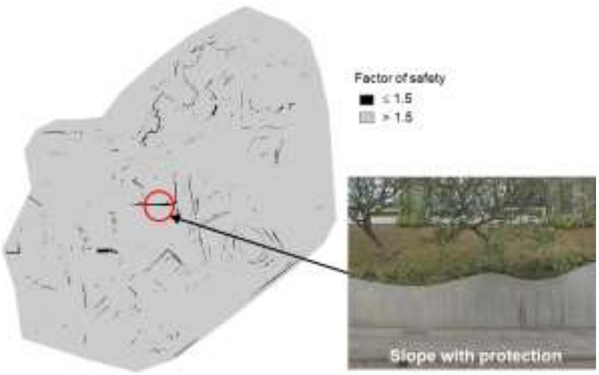

Figure 12. Generated slope susceptibility map within NTU zone with the incorporation of **unsaturated soil properties**

3 SLOPE PREVENTIVE MEASURES

Some slopes are located in the area with FOS equal to or less than 1.5 in the slope susceptibility map of Singapore in Figure 10. Those slopes may experience failures under high intensity of rainfall. Therefore, monitoring of these slopes is required to ensure that the slopes remain stable during rainy periods. The types of slope monitoring system as well as procedures of installation and maintenance are presented in this section.

Rainfall-induced slope failures may create a risk that affects the urban sustainability. Monitoring of slope is required to observe the current condition of the slope (stability, seepage, deformation) and to evaluate the effectiveness of preventive measures. Real-time monitoring will provide the earliest possible warning for possibility of slope failure. The effects of climate change (i.e. changes in rainfall intensity, amount and pattern, in groundwater level and temperature) can be incorporated in geotechnical analyses by quantifying the flux boundary conditions near the ground surface and understanding groundwater level variations through field measurements. Rahardjo et al. (2014) installed comprehensive instruments to study the effect of climate change on the stability of residual soil slopes in Singapore (Figure 13).

Common instruments for measurement of climatic data are weather station, tensiometer, piezometer, soil moisture sensor and soil temperature sensor (Rahardjo and Satyanaga, 2019). Weather station consists of apparatuses to measure rainfall intensity (rainfall gauge), wind speed, air temperature, relative humidity and solar radiation. Tensiometer is required for monitoring changes of negative pore-water pressure in the unsaturated zone. Piezometer is needed to observe the variation of groundwater table within soil layer during dry and rainy periods. Time-domain reflectometry is installed to measure the soil water content changes within soil layer whereas soil temperature sensor is required for measuring the variation of soil temperature for quantifying actual evaporation from the ground surface. All data are collected and presented in real time so that changes in the flux boundary conditions can always be calculated . A schematic diagram of typical slope instrumentation in Singapore is presented in Figure 14.

The pore-water pressure pressures contours before and after rainfall at Jalan Kukoh on 15 June 2007 are presented in Figures 15 and 16, respectively. The variations of rainfall during dry and rainy periods are incorporated into the seepage analyses as flux boundary conditions on the slope surface. The pore-water pressure changes from the seepage analyses are then used in the slope stability analyses to obtain the variations of factor of safety with time. This method can be used to quantify the effect of rainfall variations on slope stability. The factor of safety variations of slopes at Jalan Kukoh during dry and rainy periods are presented in Figure 17.

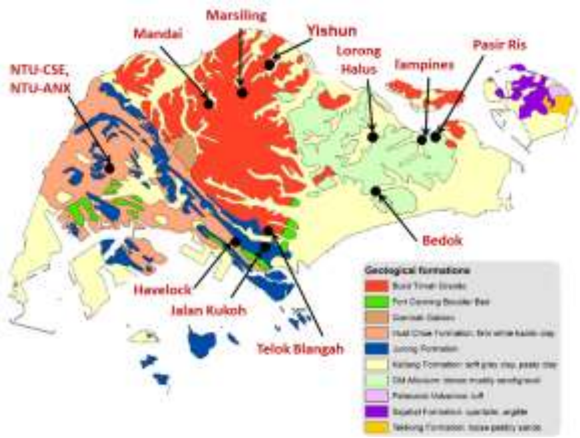

Figure 13. Locations of slope instrumentation in Singapore

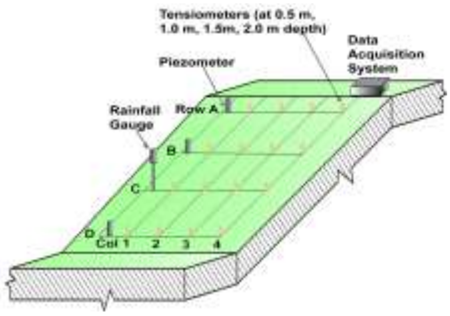

Figure 14. Schematic diagram of typical slope instrumentation in Singapore

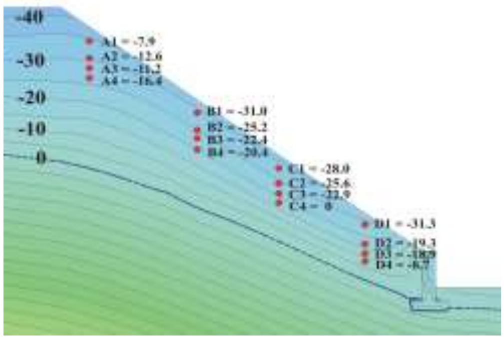

Figure 15. Pore-water pressure contours within residual soil

slope at Jalan Kukoh before rain started on 15 June 2007

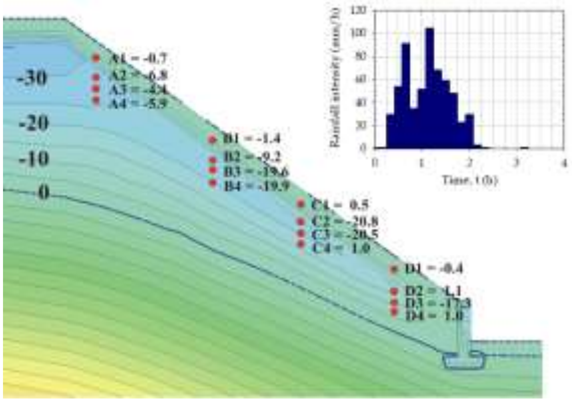

Figure 16. Pore-water pressure contours within residual soil slope at Jalan Kukoh after rain stopped on 15 June 2007

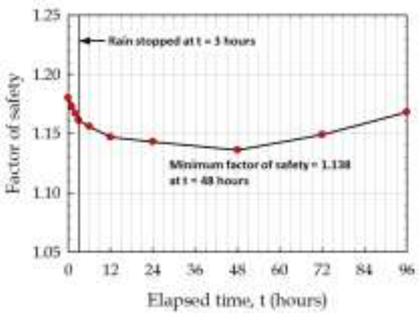

Figure 17. Factor of safety variations at Jalan Kukoh during rainfall and after rain stopped on 15 June 2007

The slopes located within the area with FOS equal to or less than 1.5 could fail during a rainfall of high intensity. Therefore, preventive measures are necessary to ensure the safety of nearby buildings or public facilities. Several slope protections against rainfall-induced slope failures that incorporate unsaturated soil mechanics principles are capillary barrier system (CBS) and geobarrier system (GBS). These methods are more economical and sustainable than the commonly used hard measures using reinforced concrete retaining wall or ground anchors. Both CBS and GBS prevent the rainwater infiltration problems directly using the capillary barrier mechanism based on unsaturated soil mechanics principles. In addition, these systems can support greenery and can be constructed using recycled materials. Hence, these systems provide a sustainable option of slope preventive measures for urban development.

3.1 Capillary Barrier System

A capillary barrier system (CBS) is commonly defined as a cover system consisting of a non-cohesive fine-grained soil overlying a coarse-grained soil (Figure 18). The difference in particle size of the fine-grained layer and the coarse-grained layer results in a large difference in the hydraulic properties (i.e. soil-water characteristic curve and permeability function) of the soils across the interface between the fine-grained layer and the coarse-grained layer. A negative pore-water pressure at the soil interface under unsaturated condition results in the lower permeability of the coarse-grained layer as compared to that of the fine-grained layer. The low permeability of the coarse-grained layer limits the downward movement of water and holds the infiltrating water in the fine-grained layer to be released through lateral diversion, evaporation and transpiration.

Numerous research works have been conducted to investigate the performances of CBSs for different applications, either through laboratory experiments (Stormont and Anderson, 1999; Tami et al., 2004; Krisdani et al., 2005; Yang et al., 2006; Huang et al., 2011; Harnas et al., 2014), numerical analyses (Morris and Stormont, 1999; Bussiere et al., 2003; Aubertin et al., 2006; Rahardjo et al., 2009a; Harnas et al., 2013; Satyanaga et al., 2019) or field studies (Khire et al., 1999; Krisdani et al., 2010; Sun et al., 2010; Zhan et al., 2014; Rahardjo et al., 2013b; Ng et al., 2015).

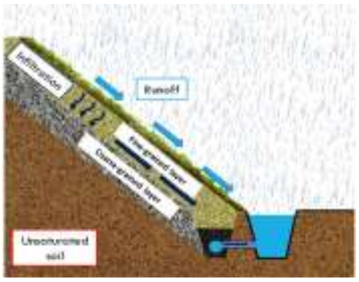

Figure 18. Schematic diagram of capillary barrier system

The CBS materials must be selected properly with careful consideration on controlling parameters of the materials in order to design an effective CBS. Rahardjo et al. (2006) carried out parametric study to obtain the controlling parameters of the CBS materials. The results show 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 (ψw-ratio), water-entry value of the coarse-grained layer and saturated coefficient permeability of the fine-grained layer. Typical SWCCs of the fine- and coarse-grained materials for CBS are presented in Figure 19.

Rahardjo et al. (2006) concluded that the minimum ψw-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 for a longer period of time. 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. Typical permeability functions of the fine- and coarse-grained materials for CBS are presented in Figure 20.

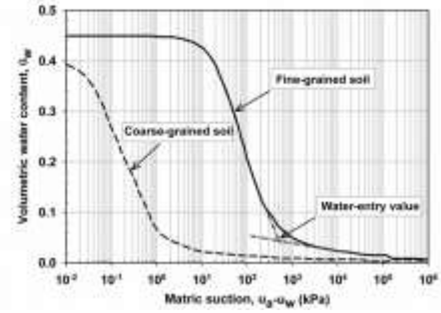

Figure 19. Soil-water characteristic curve of fine- and coarse-grained soils within a capillary barrier system

In addition to the three controlling parameters, Tami et al. (2007) concluded that the fines content within the fine-grained layer also affects 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 will increase 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 a dry period when matric suctions are high.

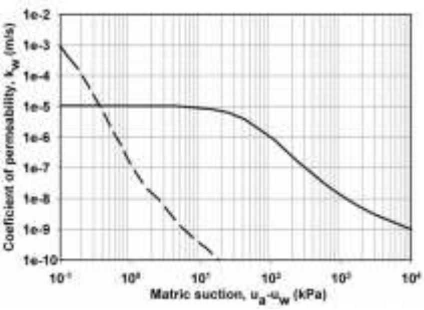

Figure 20. Permeability function of fine- and coarse-grained soils within a capillary barrier system

Rahardjo et al. (2010) instrumented a slope of residual soil from Bukit Timah Granite at Ang Mo Kio using tensiometers and piezometers. The slope experienced failures several times and had been repaired using CBS. The monitoring results showed that the slope with a capillary barrier system was able to maintain negative pore-water pressures (matric suction) under rainfall conditions. The pore-water pressures from the field instrumentation were incorporated in the slope stability analyses to obtain variations in factor of safety with time. Figure 21 shows that the factor of safety of the slope with CBS was higher than that of the original slope without CBS under the same rainfall conditions.

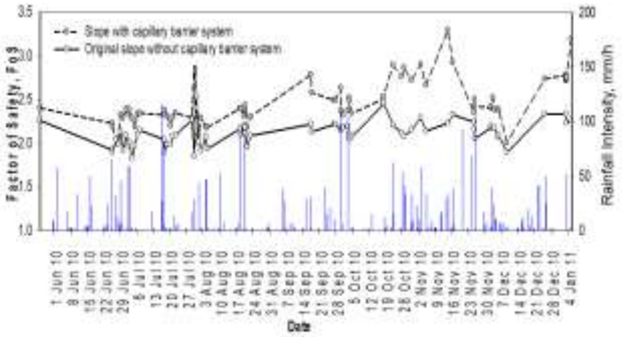

Figure 21. Factor of safety variations for slopes with and without capillary barrier system for the periods between June 2010 and January 2011

3.3 Geobarrier System

Field monitoring proved that the capillary barrier system was effective to minimize rainwater infiltration as well as maintain the stability of slope up to about 35o inclination angle (Rahardjo et al., 2010, 2012, 2013b, 2016 and Rahardjo, 2015). However, creation of new space is a growing concern in Singapore which leads to steepening slopes or cutting back slopes. The construction of slopes steeper than 35o requires consideration of a retaining structure. Thus, a retaining structure that incorporates capillary barrier system is needed to mitigate rainfall-induced failures in steep slopes under a tropical climate.

Rahardjo et al. (2015) developed Geobarrier System (GBS), a retaining structure that incorporates capillary barrier system. The system consists of geobags that are made from geosynthetics and are filled with soils or granular materials (Matsuoka et al. 2001). In line with current sustainable environmental policies, recycled materials such as recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP) can be used to replace natural aggregates as components of the capillary barrier system (Rahardjo et al. 2013; McCulloch et al. 2017). In this case, bags filled with fine-grained recycled materials (fine RCA or RAP) are placed on top of a layer of coarse-grained recycled materials (coarse RCA or RAP) as the components of a capillary barrier system. Rahardjo et al. (2018a) showed that the presence of bags between the fine- and coarse-grained materials did not interfere with the effectiveness of the capillary barrier system. Approved soil mixture (ASM) was also contained in bags and placed in front of the bags containing the fine-grained recycled materials to facilitate the planting of shrubs/trees with deep and widespread roots as part of wall facing. Geogrid is connected to the ASM bag and acts as a reinforcement in the retaining structure system. Since the geogrids are connected to the ASM bag, then the ASM bags also plays a role as the facing in the reinforced retaining structure system. The schematic diagram of GBS is presented in Figure 22.

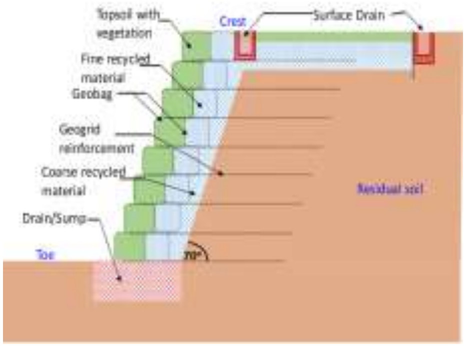

Figure 22. Schematic diagram of Geobarrier system

Two types of recycled materials, RCA and RAP of fine and coarse particles were used as materials in GBS (Figure 23). The fine-grained layer was compacted to a relative density (Dr) between 70–90 % or to the required dry density (ρd) between 1.62-1.67 Mg/m3. The coarse-grained layer was compacted to a relative density (Dr) between 70–90 % or to the required dry density (ρd) between 1.53-1.57 Mg/m3. GBS uses insitu soil as the reinforced fill. The soil should be compacted to 90% dry density based on the laboratory compaction curve of the insitu soil. The actual compaction level should be checked insitu for each placement layer of soil using sand cone test (ASTM D1556).

Geotextile used in manufacturing the geobags is made of a woven monofilament fibre weaved to form a stable matrix with high water flow and optimum opening size for soil retention. The geotextile should have a tensile strength greater than or equal to 50 kN/m at 20% strain; puncture strength of greater than or equal to 5.0 kN; pore size (O90) of less than or equal to 600 microns; and water permeability greater than or equal to 0.2 m/s. The dimension of ASM geobag is 0.6 m width × 0.5 m height × 1.5 m length while the dimension of the geobag for the fine-grained material is 0.5 m width × 0.5 m height × 1.5 m length. The ASM bag is supported by specially designed pockets for planting different types of plant. The ASM bag is also connected to geogrids that act as reinforcing elements. The bi-axial geogrids are made from high quality polyester yarn fibres with a high tensile strength of 12 kN/m @ 2% strain and 30 kN/m @ 5% strain and a design life of 120 years.

Figure 23. (a) Fine RCA; (b) Coarse RCA; (c) Fine RAP and (d) Coarse RAP used in the Geobarrier system

GBSs were constructed at Orchard Boulevard in Singapore with a slope height of 4 m and a slope angle of 70° (Figure 24). Different plant species were planted to study the survivability of the plants on the facing of the GBS. The original slope was inclined at 35°, thus the construction of the GBSs involved excavation of the slope to the designed slope angle of 70°. Preliminary site investigation indicated that the groundwater table was located at about 2 m and 6 m below the ground surface at the toe and crest of the slope, respectively. In other words, the residual soil below and behind the slope was in an unsaturated condition. The GBSs and original slope were instrumented to monitor their response to actual rainfalls. The site was instrumented with a rain-gauge to monitor rainfall and two piezometers, located near the toe and crest of the slope, to monitor the ground water table. GBS was instrumented with four pairs of tensiometers and soil moisture sensors to monitor pore-water pressure and volumetric water content, respectively. Two pairs of tensiometers and soil moisture sensors were installed vertically from the crest to monitor the pore-water pressures and moisture contents of the compacted residual soils, respectively. The other two pairs of tensiometers and soil moisture were installed perpendicular to the sloping face. In addition, two flowmeters were installed in the gravel sump beneath the GBS to measure water flow from the fine-grained layer and coarse- grained layer. The measurements by flow meters were intended to observe if there was a breakthrough from the fine-grained layer to the coarse-grained layer.

Figure 24. Different planting species for facing of the Geobarrier system

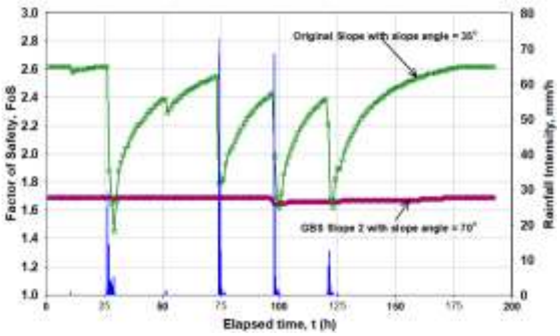

Figure 25. Factor of safety variations for slopes with and without Geobarrier system for periods between 15-Sep 2016 0:00 am and 23-Sep 2016 00:00 am

The performance of the GBSs at Orchard Boulevard was monitored for one year i.e. from 1st July 2016 to 30th June 2017. Numerical analyses were carried out to study the response of GBS in Orchard Boulevard to extreme rainfalls that occurred from 15th to 23rd September 2016. The pore-water pressure variations from field instruments at Orchard Boulevard were incorporated in the stability analyses to obtain variations in factor of safety with time. Figure 25 shows that the factor of safety of the slope protected with GBS was almost constant with time while the factor of safety of the original slope fluctuated following the rainfall events. The results indicated that the GBS performed well in minimizing rainwater infiltration into the soil behind GBS. Hence, the stability of the slope was maintained during dry and rainy periods.

4 TREE STABILITY

Trees are important components of the urban environment and provide numerous advantages to humans. Environmental condition affects tree stability and tree failure impacts the environment. This interaction requires in depth study for sustainability of tree growth within the urban environment in Singapore. Tree failure is not only a loss to the environment, it also poses a public safety risk and can lead to property damages in urban areas (Lopes et al., 2009; Schmidlin, 2009). Tree stability is particularly important in Singapore, given its planning policy that embraces the city in a garden philosophy. In an urban setting where space is limited and trees are grown alongside infrastructures, the need for strongly anchored trees becomes even more important. The stability of tree structures is due to the interaction of tree roots with the planting soil, which is at the same time exposed to constantly varying environmental parameters including rainfall. The planting soil is located within the unsaturated zone above the groundwater table. Therefore, it is important to understand the characteristics of the unsaturated soil in order to retain sufficient amount of water within the root zone for maintaining the liveability and stability of tree. The schematic diagram of the effects of environmental conditions on tree liveability and stability is presented in Figure 26.

Fine-grained soils have been commonly used as tree growing media. There have been several cases of tree failures associated with low soil strength. A mixture of fine-grained soil and coarse-grained soil has been used to overcome the challenges associated with urban trees in relation to tree stability (Grabosky and Bassuk, 1995). As compared to a fine-grained soil, the soil mixture has a higher shear strength due to an increase in contact pressure between the coarse-grained particles. In addition, the resulting macro pores allow tree roots to penetrate down to a maximum depth and this will enhance the stability of the tree and soil system. Rahardjo et al. (2008b) investigated the effectiveness of different soil mixtures using soils, namely 100 % top soil (TS), 100 % granite chips (GC), 50% granite chips and 50% top soil (50GC-50TS) and 80% granite chips and 20% top soil (80GC-20TS). The SWCC and saturated and unsaturated shear strength of each soil mixture are presented in Figures 27, 28 and 29, respectively. It was observed that the saturated and unsaturated shear strength of a soil increased significantly after mixing the soil with more than 50% of granite chips. In addition, the ability of soil mixtures in retaining moisture for tree growth at different dryness of soil can be measured through soil-water characteristic curve of the mixtures based on unsaturated soil mechanics principles (Figure 27). It appeared that the soil mixtures 50GC-50TS and 80GC-20TS had moisture retention capability in between those of top soil and granite chips.

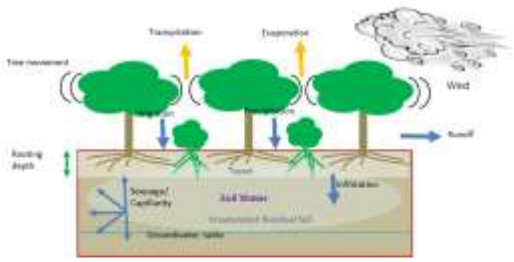

Figure 26. Effects of environmental conditions on tree livability and stability

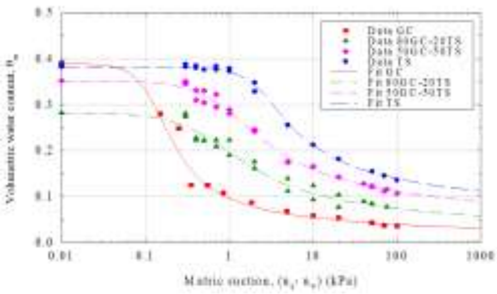

Figure 27. SWCCs of the granite chip (GC), top soil (TS), and

soil mixtures of 80% granite chip-20% top soil (80GC-20TS) & 50% granite chip-50% top soil (50GC-50TS)

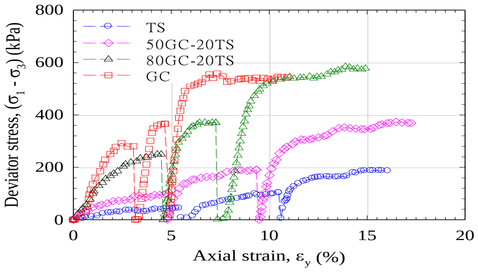

Figure 28. Shear strengths of the granite chip (GC), top soil (TS), and soil mixtures of 80% granite chip-20% top soil (80GC-20TS) & 50% granite chip-50% top soil (50GC-50TS)

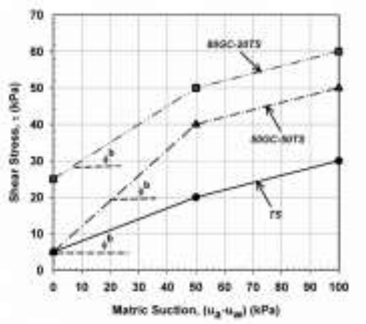

Figure 29. Unsaturated shear strengths of top soil (TS), soil mixtures of 80% granite chip-20% top soil (80GC-20TS) and 50% granite chip-50% top soil (50GC-50TS)

Previous studies of tree root systems showed that the strength of tree root anchorage is governed by several factors, such as root architecture (Dupuy et al., 2005; Fourcaud et al., 2008), soil properties (Dupuy et al., 2005), depth, shape and weight of soil root plate (Coutts, 1986), and the location of the rotational axis during overturning (Mickovski and Ennos, 2002; Fourcaud et al., 2008). Tree pulling tests had been conducted on trees to study the mechanism associated with tree failures (Peltola, 2006). However, tree pulling is costly and destructive. Therefore, the number of trees that can be pulled to study the mechanism of tree failure is often limited.

Rahardjo et al. (2014b) carried out pulling out test to investigate the overturning process of rain trees that were planted in top soil (TIF), insitu residual soil (IIF) and soil mixtures between granite chips and top soil (GC-TS). The results obtained from the tree pulling test was compared with the results generated from analytical calculations and numerical models for the different soil types. The experiment was conducted on an open land in the western end of Singapore. A total of 20 rain trees had been planted for three years, each in a tree pit of 2.5 m x 2.5 m and 1.0 m depth. Before conducting the tree pulling test, several tree characteristics such as girth circumference, tree height, stem volume and crown width were recorded. The tree pulling test was conducted using an automated winch (Ingersoll Rand-FA7) which was capable of providing a maximum load of seven (7) metric tons (Figure 30). The setup of the tree pulling test is presented in Figure 31. Uprooting was the only mode of failure observed in all 20 rain trees. The uprooting was characterized by the lifting of the intact root plate with the tree eventually falling under its own weight.

Figure 30. Tree pulling test set up in the field

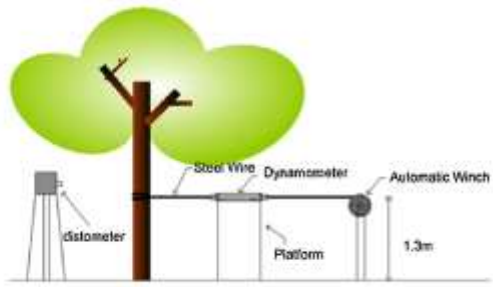

Figure 31. Schematic diagram of tree pulling test set up

Study by Rahardjo et al. (2014b) concluded that (a) both crown and root characteristics can have implications on the anchorage and stability of a tree regardless of soil type (e.g. soil mixtures or natural soils) and (b) the soil mixtures (50GC-50TS and 80GC-20TS) did not negatively affect the growth performances of the trees planted within the mixtures. Figure 32 indicates that the stability of tree increases linearly with the volume of root plate. A higher maximum pulling force is required to fail the tree with the larger volume of root plate. The findings from this study also suggested that the use of soil mixtures as a planting medium could be a viable option.

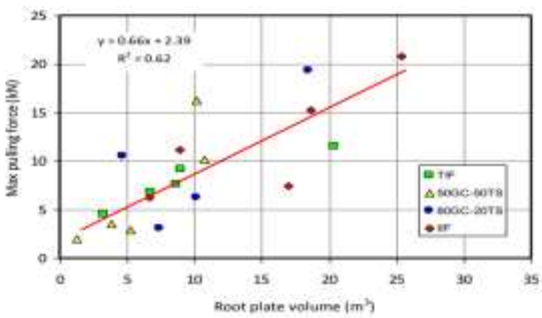

Figure 32. Relationship between root plate volume and maximum pulling force for different soil mixtures (top soil (TIF),

insitu residual soil (IIF) and soil mixtures (50%granite chips-50%top soil or 50GC-50TS and 80%granite chips-20%top soil or 80GC-20TS)

5 CONCLUSIONS

The following conclusions can be derived from this paper:

1. The unsaturated soil mechanics and the properties of unsaturated soils are required in the development of slope susceptibility map for sustainable urban development.
2. The capillary barrier system and geobarrier system using the principles of unsaturated soil mechanics and incorporating recycled materials have been shown to be effective in minimizing rainwater infiltration into slopes and preventing slope failures.
3. The unsaturated soil mechanics principles are required in designing the appropriate soil mixtures for maintaining tree stability during dry and rainy periods.

ACKNOWLEDGEMENTS

The works described in this paper were supported by the Housing and Development Board (HDB), Building and Construction Authority (BCA), National Parks (NParks), Singapore Land Authority (SLA) and Nanyang Technological University, Singapore.

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