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Stability of Unsaturated Soil Slopes Covered with *Melastoma*

Malabathricum in Singapore

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ABSTRACT:

Past studies showed that slopes covered with vegetation are less susceptible to rainfall-induced slope failures. This paper focused on unsaturated properties of soil consisting roots of Mangrove and their effects on stability of soil slope from Old Alluvium during rainfall. *Melastoma Malabathricum* was selected in this study since this Mangrove is best suited for tropical climatic condition. The results of laboratory tests indicated that the air-entry value and shear strength of the soil with roots of *Melastoma Malabathricum* were higher than those of the soil without roots. The saturated permeability of the soil with roots was lower than that of the soil without roots. The numerical analyses indicated that slope without *Melastoma Malabathricum* experienced significant decreases in factor of safety during rainfall than slope covered with *Melastoma Malabathricum*. Hence, *Melastoma Malabathricum* can be used as a vegetative cover in minimizing rainwater infiltration slope layers with slope angle up to 35°.

Keywords: Slopes; Stabilisation; Laboratory Tests; Vegetation; Numerical Modelling

1. INTRODUCTION

Despite many debates about the existence of global warming, over 97% of climatologists came into agreement that climate change is significantly affected by human

activities (Doran & Zimmerman, 2009). A study on one aspect of climate change by Strauch et al. (2017) indicated that the changes in climatic conditions may result in a higher rainfall intensity with a shorter period of rainfall in the future. Moreover, more water vapour is retained in the atmosphere due to the increase in average air temperature, which causes an exponential increase in the water vapour carrying capacity of the air (O'Hare et al., 2005). Consequently, landslide events have been shown to increase considerably due to this shift to increasing rainfall amounts and rainfall intensity (Ciabatta et al., 2016).

A review of various publications on changes in climatic conditions in the world shows that all countries experienced a higher rainfall intensity, while the trend in annual rainfall varies greatly across different geographies. Brazil experienced more frequent rainfalls with an intensity higher than 100 mm/day and less frequent rainfalls with an intensity lower than 20 mm/day (Lacerda et al., 2015). Similarly, heavy precipitation days (>10mm) and the number of very wet days (>95th percentile of historical precipitation threshold) in Canada are projected to increase (Cloutier et al., 2015). Moreover, research in Switzerland indicated that the increase in temperature was attributed for the reduction of snow and ice cover in the Alps (Beniston et al., 2006), which may accelerate glacier retreat and melt the upper layers of the permafrost, increase landslide hazards, especially debris flows, even without precipitation.

Data from Barnaul landslide-prone region in Russia showed that landslide activation is directly correlated with rainfall intensity (Zerkal & Strom, 2015), affirming the close relationship between more intense precipitation and increased frequency of landslides. Rainfall has been identified as the main landslide-triggering mechanism and the main cause of reactivation of dormant slides in Spain (Corominas et al., 2015). Similarly, Kalsnes et al. (2015) has identified surface erosion during short intense storm and slow build-up of pore-water pressure over longer periods of lower intensity rainfall to be the main causes of most landslides in Norway. Picarelli et al. (2015) in Italy also echoed the same message that higher triggering

precipitation events require lower cumulative 29-day antecedent precipitation. Moreover, in UK, it has been observed that majority of landslides were triggered by certain number days of rainfall followed by a significant rainfall intensity prior to the day of the landslide (Dijkstra et al., 2015).

Climate change in Asia seems to echo the global climate change trend in terms of the increase in average temperature, the changes in total annual precipitation, and the increased frequency and intensity of rainfall. Rainfall has been identified as the final triggering factor for landslides in Thailand (Rahardjo et al., 2014b). Wang and Towhata (2015) from Japan observed that increasing number of landslides was correlated with the increasing intensity of precipitation. In Hong Kong the density (number of occurrence per km²) of natural terrain landslides increased exponentially with the normalised rainfall intensity (Ho et al., 2015). Furthermore, the number of landslides in Taiwan has increased sharply in the last two decades, which coincides with an increase in precipitation (Meei-Ling et al., 2014).

Most landslides in Asia tend to be shallow slides (<4 m deep) within the unsaturated zone above groundwater table. Majority of landslides occurred during or immediately after intense rainfall. Rahardjo et al. (2013) found that 40-100% of the rainfall amount infiltrated into residual soil slopes. Since most exposed slopes in Singapore consist of unsaturated residual soil, it is necessary to protect this zone from rainwater infiltration for maintaining the stability of slope during heavy rainfalls. Soil-bio engineering techniques by covering the slope surface with vegetation has been employed in Singapore (Rahardjo et al., 2018), Hongkong (Ng et al., 2016; Leung et al., 2015), Thailand (Jotisankasa and Sirirattanachat, 2017), Malaysia (Osman and Barakbah, 2006).

Vegetation can also enhance the stability of a slope by root reinforcement. Wu et al. (1979) investigated the stability of slopes before and after removal of forest cover and concluded that the shear strength contributed by tree roots is important to the stability of slopes.

The study indicated that vegetation could contribute shear strength to the slopes through root reinforcement. Wu et al. (1979) showed that slope failure would have occurred if the effects of vegetation were not taken into account in slope stability analyses.

Gray and Ohashi (1983) carried out direct shear test on a dry sand reinforced with different type of fibers. The results indicated that fiber reinforcement increased the peak shear strength of the sand. The findings are relevant to the contribution of root reinforcement to the stability of sandy slopes. Other researchers (Michalowski & Zhao, 1996; Zornberg, 2002; Michalowski & Cermák, 2003; Heineck & Consoli, 2004; Gao & Zhao, 2013) have carried out theoretical studies to develop predictive models of the improvement of shear strength due to the addition of fibers in the soil. Bovolenta et al. (2018) investigated the contribution of soil bio-engineering techniques in protecting the slope from shallow landslides. They observed that the mechanical contribution of plants enhanced the performance of cribwalls in term of the increments in the factor of safety of the structure.

Shrubs are commonly used as vegetative cover since they are able to induce a significant reinforcing effect in soil down to depths of 0.5 m - 1.5 m which is a typical depth of instability. Therefore, the implementation of vegetation cover will help to hold the soil together and prevent the degradation of the slopes. The plant roots have the ability of binding the soil composite and causing adhesion of the soil particles to the roots, therefore increasing the soil strength (Ali and Osman, 2008). The introduction of vegetation to improve slope stability was of lower cost as compared to other methods like soil nailing and improved drainage (Rahardjo et al., 2014; 2018). The fine roots will enhance the cohesion in the soils by introducing the additional cohesion, thus increasing the effective cohesion, c' , in the soil (Greenwood et al., 2004).

In countries with a tropical climate like Singapore, the amount of heavy rainfall is very high and the global warming attributes to higher rainfall intensity within shorter period of time.

During heavy rainfalls the pore-water pressure or matric suction and the shear strength of unsaturated soil slopes changes, resulting in many slope failures (Rahardjo et al., 2013). The variations in the flux boundary due to infiltration, evaporation and transpiration greatly affect the negative pore-water pressure. One way to prevent rainfall-induced slope failures is to use the green technology which incorporates engineering design method using vegetative cover to improve the stability of slopes (Rahardjo et al., 2014a). The objective of this project is to investigate the effects of *Melastoma Malabathricum* in improving the stability of slopes near riverbank in Singapore. The scope of work includes the measurement of saturated and unsaturated properties of the soil with and without roots of *Melastoma Malabathricum*. Furthermore, the numerical analyses were performed to observe the variations in factor of safety of the slope with and without *Melastoma Malabathricum* along the riverbank.

2. SOIL CHARACTERIZATION

2.1 Site Study

The soil samples for this study were collected from the investigated slope near a riverbank located in the Punggol area in Singapore within the residual soil from Old Alluvium (Figure 1). The slope was covered with the selected type of Mangrove, *Melastoma Malabathricum* which was planted within the approved soil mixture (ASM) layer. ASM is the soil mixture comprising an appropriate volume of top soil, sand, soil conditioner, organic compost which are approved by regulatory board in Singapore to enable liveability of plants in long term. This type of Mangrove was chosen since it is best suited to tropical climatic country such as Singapore (Shufen et al., 2011). *Melastoma Malabathricum* (Figure 2) is part of the Melastomataceae family which is categorized as a shrub (Omar et al., 2013). This type of mangrove may grow up to 3 m tall. The leaves are simple (the leaves' blade or lamina is undivided into lobes), narrow with 3 prominent longitudinal veins.

According to Public Works Department (1976), majority of coarse sands with certain amount of clay particles cover almost all parts of soils located at Old Alluvium. A study by Rahardjo et al. (2012) indicated that typical residual soils from Old Alluvium are associated with high percentages of sand where the lateral and vertical distribution of its particle size are more uniform as compared to other formations. Rahardjo et al. (2012) also observed that the shear strength of the residual soil from Old Alluvium is higher than those of the residual soils from other formations in Singapore.

2.2 Index Properties

The water content and organic content tests were performed to evaluate the percentage of roots within the soil. The organic content test was carried out according to ASTM D2974-14 where the oven-dried specimen was placed in a muffle furnace with a temperature of 440⁰C until there was no further change in soil specimen mass. The index properties of soil specimens with and without roots were obtained from the specific gravity test (ASTM D854-14), grain size distribution test and hydrometer analysis (ASTM D422-63) as well as Atterberg limits test (ASTM D4318-17). Triaxial cell with the application of two different pore-water pressures (ASTM D5084-16) were utilized to generate the saturated permeability of soil. The classifications of the soil specimens were carried out based on the Unified Soil Classification System (USCS) in ASTM D2487-00.

2.3 Soil-water Characteristic Curve

The undisturbed soil samples of ASM were collected from depths of 0.5 m. In addition, the undisturbed soil samples of residual soil were collected from depths of 2.0 m. The specimens were trimmed to a diameter of 50 mm and were cut to the required heights for different tests (30 mm height for SWCC, saturated permeability and shrinkage tests; 100 mm

height for saturated and unsaturated shear strength tests). In this study, a small-scale centrifuge (Figure 3) was utilized to determine the SWCC (ASTM D6836-02). This method was selected since it was faster than the conventional pressure extractor method. The saturation of the specimen with and without roots were carried out by introducing the water from the top and bottom of the specimen through the filter paper within the specimen holder. The specimen was confined by a steel ring which was placed inside the holder (see Figure 3a). Prior to the test, two saturated specimens were weighed and placed in the centrifuge cell. The mass of the two specimens must be similar to maintain the balance of the machine. Different soil suctions were applied by varying the angular velocity for a specified duration. The mass of the specimen upon completion of each rotation according to a certain angular velocity, was measured to determine the SWCC data points. Centrifuge can be used to apply soil suctions between 0.01 kPa (0 rpm) and 250 kPa (3900 rpm).

Determination of soil suction in the SWCC test using the centrifuge was carried out using Equation 1 as proposed by Gardner (1937) (Khanzode, et al., 2002).

$$\psi = \frac{\rho\omega^2}{2}(r_1^2 - r_2^2) \quad (1)$$

where: ψ = soil suction (kPa), r_1 = the length from the center of centrifuge to the center of the soil specimen (m), r_2 = the length from the center of centrifuge to the free water surface (m), ω = angular velocity (rpm), ρ = density of water (kg/m^3).

The chilled-mirror hygrometer (WP4C) (Figure 3b) was used to determine the SWCC data points for suctions above 500 kPa (ASTM D6836-02). One (1) specimen was used for measurement of suctions beyond 500 kPa using chilled-mirror hygrometer apparatus. A cutter with a diameter of 4 cm was used to trim the specimen with and without roots for WP4C test. The specimen was placed inside the steel cup which was weighed prior to the test. Then, the cup was placed into a temperature-controlled chamber. The apparatus measures the dew point temperature by reducing the temperature of a mirror in the chamber until condensation

occurred. At the end of the test, the specimen was completely dried to determine the mass of solid of the specimen. The soil suction from the chilled mirror hygrometer test was determined based on Kelvin equation (Equation 2).

$$\psi = \frac{-RT_k \rho_w}{\omega_v} \ln \left(\frac{u_v}{u_{v0}} \right) \quad (2)$$

where: ρ_w = density of water, kg/m³, u_v = partial pressure of pore-water vapor (kpa), R = universal (molar) gas constant [i.e., 8.31432 J/(mol K)], T = temperature, °C, T_k = absolute temperature (i.e., $T_k = 273.16 + T$, K), ω_v = molecular mass of water vapor (i.e., 18.016 kg/kmol), u_{v0} = saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa).

Shrinkage tests were performed to determine the changes in total volume and void ratio of the specimens as gravimetric water content decreases. The total volume and void ratio of the specimen were plotted against gravimetric water content. Hence, an SWCC plotted with gravimetric water content can be converted into one with volumetric water content or degree of saturation. The studies by Fredlund et al. (2002) and Zhai and Rahardjo (2012) indicated that the variables of SWCC should be determined based on SWCC in terms of degree of saturation.

The SWCC data from laboratory tests were established in term of discrete points. For incorporation of SWCC data into numerical analyses, the best fitting equation was required to develop continuous line of SWCC. In this study, Fredlund and Xing (1994) equation (Equation 3) was used to best fit the SWCC data. Leong and Rahardjo (1997) suggested a correction factor = 1 to be incorporated in the Equation 3 for SWCC of residual soils in Singapore.

$$S_r = C(\psi) \left\{ \frac{100}{[\ln\{e + (\frac{\psi}{a})^n\}]^m} \right\} \quad (3)$$

where,

S_r = degree of saturation for different soil suction (%),

200 e = natural number, 2.71828...,

201 a, n, m = fitting parameters of Fredlund and Xing (1994) equation,

202 $C(\psi)$ = correction factor = 1.

203

204 2.4 Permeability Function

205 The direct measurement of unsaturated permeability is more time-consuming and
206 complex (Samingan et al., 2005). As a result, the indirect measurement is more preferred by
207 developing a relationship between unsaturated permeability and SWCC. The statistical model
208 is commonly used in the determination of permeability function whose equation was proposed
209 by Childs and Collis-George (1950) and later improved by Kunze et al. (1968) as shown in
210 Equation 4.

$$211 \quad k_w = \frac{k_s}{k_{sc}} A_d \sum_{j=i}^m \left[\frac{2j+1-2i}{(u_a-u_w)_j^2} \right] \quad (4)$$

212 where

213 k_s = measured saturated permeability (m/s)

214 k_{sc} = calculated saturated permeability (m/s)

215 A_d = adjusting constant to take into account the effect of surface tension, density, viscosity
216 of water and porosity of soil which can be considered as unity

217 m = total number of intervals between the saturated and lowest volumetric water content
218 on the SWCC data

219 i = interval number which increases with the decreasing volumetric water content

220 j = a counter from “i” to “m”

221 $(u_a-u_w)_j$ = matric suction corresponding to the midpoint of the j^{th} interval.

222

223

224

2.5 Unsaturated Shear Strength

In this study, saturated and unsaturated shear strength tests were carried out using multistage testing to expedite the testing process where the loading and unloading procedures were imposed on soil specimen continuously. The maximum allowable cumulative axial strain is limited to 20% according to Goh et al. (2010). Consolidated-undrained (CU) triaxial tests with pore-water pressure measurement were conducted to obtain shear strength parameters for the soil under saturated condition. A shearing rate of 0.05 mm/min was selected during shearing process of soil with high percentage of sand according to ASTM D4767-11.

A modified triaxial apparatus (Figure 4) was used for the multistage consolidated-drained (CD) shear strength test of unsaturated soil following the procedure explained by Fredlund and Rahardjo (1993). A 50-mm high air-entry ceramic disk with a capacity of 5 bar was used and placed on the pedestal of the modified triaxial apparatus. A strain rate of 0.0009 mm/min was used to avoid the built-up of pore-water pressure during shearing process as suggested by Rahardjo et al. (2004). The unsaturated shear strength tests were carried out under a net confining pressure of 25 kPa and matric suctions of 25 kPa, 50 kPa and 75 kPa.

This study used Fredlund et al. (1978) equation (Equation 5) to determine the unsaturated shear strength parameters of a soil.

$$\tau = c' + (\sigma_f - u_w) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (5)$$

where,

τ = shear strength of an unsaturated soil (kPa),

c' = effective cohesion of the soil (kPa),

ϕ' = angle of internal friction associated with the net normal stress state variable ($^\circ$),

ϕ^b = angle indicating the rate of increase in shear strength relative to matric suction ($^\circ$),

σ = normal stress (kPa),

u_a = pore-air pressure (kPa),

250 u_w = pore-water pressure (kPa),

251 $(\sigma - u_a)$ = net normal stress (kPa), and

252 $(u_a - u_w)$ = matric suction (kPa).

253

254 3. LABORATORY TESTING RESULTS

255 The index properties of the residual soil from Old Alluvium, ASM with roots and ASM
256 without roots are presented in Table 1. The organic content of the specimen with roots (6.6 %)
257 is higher than that without roots (0.8%) indicating the significance presence of roots within the
258 soil samples taken from ASM soil below *Melastoma Malabathricum*. The specimen with roots
259 has more clay particles as compared to specimen without roots which might be caused by the
260 biochemical response among plants and soils. The main mineral of soil, such as: feldspars,
261 biotite, quartz and muscovite) could be destroyed by the acids from root metabolism. Hence, a
262 higher percentage of clay particles might be formed within soil-root zone (Schoonover and
263 Crim, 2015).

264 The specimen without roots has a lower density than specimen with roots. This
265 indicates that the pores of specimen with roots are filled with the roots contributing to the
266 higher mass of specimen under the same volume. As a result, the water is more difficult to flow
267 within specimen with roots resulting in the lower permeability of specimen with roots as
268 compared to specimen without roots. This result is in agreement with the results of the studies
269 by Ahmed et al. (2018) and Meyer et al. (2010) that showed the roots presence affects the water
270 flow within soil layer. The larger amount of clay particles within specimen with roots is also
271 associated with the higher plastic limit of specimen with roots as compared to specimen without
272 roots. Figure 5 shows the SWCC of the residual soil from Old Alluvium, ASM with and
273 without roots. The air-entry value (AEV) of the residual soil is very low (1.1 kPa) and the slope
274 of SWCC for the residual soil is very steep. This is attributed to the high percentage of sand

within the residual soil (93.5 %). The AEV of the ASM with roots (1.6 kPa) is lower as compared to that of the ASM without roots (9 kPa). This may occur since the specimen with roots experienced significant volume change which was attributed to the growing of roots during 1 week saturation process of the soil specimen within the specimen holder prior to centrifuge test. As a result, the desaturation process of the specimen with roots started earlier as compared to that of the specimen without roots. The slope of SWCC for the specimen with roots is gentler than that of the specimen without roots indicating the pore-size distribution within specimen with roots is more distributed as compared to that without roots. This may be caused by the modifications of soil pores attributed to the existence of roots between soil pores.

The permeability functions of residual soil, ASM without and with roots are presented in Figure 6. The residual soil has the highest permeability as compared to ASM with roots and without roots under the saturated condition since the specimen from the residual soil has the highest percentages of sand particles. Permeability of ASM without roots is higher than that of ASM with roots under saturated and unsaturated conditions. This may be attributed to the lower percentages of clay particles resulting in the larger pore sizes within the specimen without roots as compared to that of the specimen with roots. As a result, it is much easier for water to infiltrate into the specimen without roots than into the specimen with roots under the saturated and unsaturated conditions.

The results from the saturated and unsaturated shear strength tests (Table 2) indicate that the specimen without roots has a lower effective cohesion ($c' = 3$ kPa) as compared to specimen with roots ($c' = 9.5$ kPa). This observation is in line with the the results of the study by Kokutse et al. (2016) where the existence of roots contributed to the additional strength of soil, called root cohesion. The specimen without roots has similar effective friction angle ($\phi' = 30^\circ$) with the specimen with roots ($\phi' = 32^\circ$). This could be attributed to the same amount of sand particles within specimen without and with roots (60 %). The ϕ^b value of the specimen

with roots is similar to that of the specimen without roots. This indicates that the presence of roots that act as fibres only has significant effect on the additional cohesion of soil.

4. NUMERICAL ANALYSES

Numerical analyses were performed to investigate the performance of *Melastoma Malabathricum* against rainfall-induced slope failures for different slope angles. In this research work, SEEP/W software (Geoslope International Ltd., 2012) was utilized to perform transient seepage analyses in order to understand the characteristic of pore-water pressures variations within slope with and without mangrove during dry and rainy periods. SLOPE/W software (Geoslope International Ltd., 2012) was utilized to perform stability analyses to observe the changes in factor of safety of slopes with and without mangrove during dry and rainy periods. Six cases of numerical analyses with the actual slope height on site (6 m) were conducted in this study (Table 3).

Simplified slope profiles with a residual soil properties from Old Alluvium at Slope A (same SWCC and permeability function for all the elements) were used in all cases. In cases 1 to 3, the slopes were covered with ASM with roots of *Melastoma Malabathricum* whereas in cases 4 to 6, the slopes were covered with ASM without roots of *Melastoma Malabathricum*. The soil with root was considered as deep as 0.5 m in the seepage analyses. A rainfall of 22 mm/h for 24 hours (PUB, 2009) followed by no rainfall for another 24 hours was applied on the surface of the slope model.

The numerical model for all cases in the analyses is presented in Figure 7. The finite element mesh was developed based on combination of triangular and rectangular elements. The loading from rainfall was incorporated in the analysis as a flux boundary, q , on the slope surface. The left and right sides of the model above the groundwater table were simulated as no flow boundaries ($Q = 0$). The left and right sides of the model below groundwater table were

simulated as constant total head (h_w). During rainfall, cumulation of water on the ground surface was not allowed in the model to represent the actual condition where runoff occurs during rainfall. In other words, the pore-water pressure was not allowed to be larger than 0 kPa at the ground surface of the model. SEEP/W utilized Darcy's law (Equation 6) to determine the water flow through saturated and unsaturated soil layers (Fredlund and Rahardjo, 1993).

$$\frac{\partial}{\partial x} \left(k_w \frac{\partial h_w}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_w \frac{\partial h_w}{\partial y} \right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t} \quad (6)$$

where,

$\frac{\partial h_w}{\partial x}$ = hydraulic head gradient,

k_w = coefficient of water permeability with respect to soil suction in both x-direction and y-direction, and

m_2^w = coefficient of volume change with respect to water for different soil suctions (slope of SWCC).

h_w = hydraulic head; y and x = the coordinates in the y- and x-directions, respectively; t = time (second); ρ_w = bulk density of water (Mg/m^3); g = gravitational acceleration (m/s^2).

The stability analyses of residual soil slopes under different conditions were performed with the incorporation of pore-water pressures changes from the seepage analyses. The saturated and unsaturated shear strength parameters of soils investigated in this study as shown in Table 2 were used in Slope/W for the stability analyses involving different conditions of residual soil slopes. The factors of safety at different time increments were calculated using Bishop's simplified method of slices. The variations in factor of safety with time for different slope angles for slopes with and without mangrove are presented in Figure 8.

Figure 8 shows that the initial factors of safety of the slopes with mangrove and slope angles of 27° , 35° and 45° are 1.5, 1.28 and 1.1, respectively. On the other hand, the initial factors of safety of the slopes without roots and with slope angles of 27° , 35° and 45° are 1.48, 1.22 and 0.6, respectively. It can be observed that there is almost no difference between the

initial factors of safety for the slopes with and without roots with slope angles of 27°. The difference in the initial factors of safety becomes larger as the slope becomes steeper. This indicates that mangrove plays more significant roles in strengthening steep slopes as compared to gentle slopes. Figure 8 also indicates that the decreases in factor of safety for the slopes with mangrove are about the same for different slope angles (around 1.5). The decreases in factor of safety for the slopes without mangrove and with 27°, 35° and 45° of slope angle are also about the same (around 2.0). Figure 8 also shows that the factor of safety of 45° of slope angle with mangrove started to decrease to a value below one after 8 hours of rainfall. Therefore, mangrove was considered to be effective in maintaining the stability of slope during rainfall for slopes with a slope angle up to 35°.

5. CONCLUSIONS

- The experimental works in laboratory show that:
 - The air-entry value and the saturated permeability of soil with roots of *Melastoma Malabathricum* are lower than soil without roots of *Melastoma Malabathricum*.
 - The shear strength of soil with roots of *Melastoma Malabathricum* is higher than soil without roots of *Melastoma Malabathricum*.
- The results from numerical analyses indicate that *Melastoma Malabathricum* can be used as a slope cover to minimize rainwater infiltration into slope and to maintain the slope stability during rainfall.
- *Melastoma Malabathricum* is effective to be used as a slope cover for slopes with an inclination angle of less than 35°.

372

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378

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Index properties	Residual soil	ASM without roots	ASM with roots
Organic content (%)	0.4	0.8	6.6
Gravel (%)	3.3	9	0
Sand (%)	93.5	61	60
Silt (%)	0	19	13
Clay (%)	3.2	11	27
Total density, ρ (Mg/m ³)	1.585	1.704	1.758
Liquid limit, LL (%)	-	47	47
Plastic limit, PL (%)	-	23	29
Saturated permeability, k_s (m/s)	8.7e-5	7.9e-6	1.5e-6
USCS classification	Poorly Graded Sand (SP)	Clayey Sand (SC)	Silty Sand (SM)

Table 2. Shear strength properties of residual soil, ASM without and with roots

Shear strength properties	Residual soil	ASM without roots	ASM with roots
Effective cohesion, c' (kPa)	2	3	9.5
Effective friction angle, ϕ' (°)	29	30	32
ϕ^b angle (°) for $\psi \leq \text{AEV}$	29	30	32
ϕ^b angle (°) for $\psi > \text{AEV}$	5	15	17

Table 3. Parametric study to investigate the effect of mangrove on slope stability

Case	1	2	3	4	5	6
Slope Angle (°)	27	35	45	27	35	45
Slope Height (m)	6	6	6	6	6	6
Slope condition	With roots	With roots	With roots	Without roots	Without roots	Without roots

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