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ASSESSMENT OF RESIDUAL SOIL PROPERTIES FOR SLOPE STABILITY ANALYSIS

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ABSTRACT: Slope instability is a common natural geological hazard in tropical countries like Malaysia, with abundant residual soil and frequent rainfall. Over the years, these rainfalls have induced instabilities that lead to significant human and economic loss. To reduce the expected disastrous impacts due to rainfall-induced slope failure characterization of residual soil is necessary for evaluation of slope stability assessment. Therefore, this study aims to characterize the residual soil for numerical modelling of rainfall-induced slope failure and preliminary slope stability assessment so that future slope failure can be reduced. A series of experiments involving index properties tests and engineering properties tests were carried out on the residual soil samples collected from a slope located in Universiti Teknologi Malaysia (UTM). Based on the particle size distribution and consistency the soil can be classified as high plasticity silt (MH). The maximum dry unit weight and optimum moisture content are 13.17kN/m3 and 30 %, respectively. Saturated hydraulic conductivity from the falling head test is 2.32055E-07 m/s, while the saturated gravimetric water content was 54%. The effective cohesion and angle of the internal fraction were 8 kPa and 32°, respectively. The average undrained shear strength and unconfined compressive strength were 105 kPa and 43 kPa, respectively. The result obtained in this study was utilized for the preliminary rainfall slope stability assessment in tropical residual soils by simulating rainfall of different intensities and duration on a typical slope profile using PLAXIS 2d. The results show that due to the low hydraulic conductivity and fine-grained nature of the soil, the slopes in the study area are more critical to the low intensity and long duration rainfall events ($I \leq 4Ks$). The highly intense and short-duration rainfall ($I \geq 8Ks$) has no significant effect on the safety of the soil, as most of the precipitation will contribute to runoff, and only a minor amount of water will infiltrate into the slope.

Keywords: Residual soil, Slope Instability, Rainfall, Plaxis 2D

1. INTRODUCTION

Slope instability is a major geological hazard occurring all over the world, leading to a great economic and human loss. These slope instabilities are very common in tropical countries especially during rainfall [1]. The warm to hot climate together with heavy rainfall facilitates the formation of residual soil as a result of which thick layers of residual soils are found in the tropical regions [2]. The high frequency of the slope instabilities in these tropical regions are due to two major factors, very intense and frequent rainfall, and the natural characteristics of residual soil [3]. Malaysia is located in tropical region where average temperature and annual mean rainfall is high, therefore more than 3 quarters of its land is covered by residual soil [4]. As a result, most of the slope instability arises in residual soils especially during rainfall. In the period 1993-2011, about 28 major slope failures have been reported in Malaysia which resulted in a loss of 100 precious lives. Similarly, during the period 1973-2007, the economic loss due to slope failure in Malaysia has been estimated to be about US $1 billion [5]. In recent years, Penang and Cameron Highland are severely hit by rainfall induced landslides, with a landslide in Tanjung Bungah [6] and Bukit Kukus road project[7] claiming the lives of 11 and 9 workers, respectively.

Although rainfall induced slope instabilities have been occurring over the years, yet there is lack of data regarding the properties of residual soil for the assessment of rainfall induce slope failures. Therefore, the objective of this study is to classify the residual soil, characterise and determine the index and engineering properties. The index properties such as grain size distribution, Atterberg's limits, specific gravity, and engineering properties such as shear strength parameters, saturated hydraulic conductivity and soil water characteristic curve were determined and later used in preliminary slope stability assessment of rainfall induced failure using Finite element analysis software PLAXIS. The results obtained in this study contributes to the existing literature on characteristics of residual soil and can be used by design engineers for preliminary slope stability assessment, numerical modelling of the slope and slope stability related problems.

2. RESEARCH SIGNIFICANCE

In this paper the authors have attempted to characterize the properties of residual soil from tropical region for preliminary rainfall induced slope stability assessment. The results of soil properties obtained during this study have been simulated in 2d Finite element software (PLAXIS) to assess the stability of slopes under rainfall events of different intensity and duration in the study location.

3. BACKGROUND

The properties of residual soil are very complex and vary from place to place depending upon degree of weathering, climate, and topography. Therefore, to properly assess the behaviour of residual soil for any region it should be studied individually [8]. Various researchers have attempted to characterise the tropical residual soil [8-11] But there is still lack of in-depth study of characterizing the residual soil for unsaturated slope stability assessment.

Most of the tropical residual soil slopes exist in unsaturated condition and are characterised by deep water table. Due to the warm and humid climate of tropics water is extracted out of the ground by evaporation or through evapotranspiration from the vegetative cover [12]. As a result, a very thick unsaturated zone forms which results in negative pore water pressure (matric suction) above the water table [3, 13]. Slope in these residual soils is usually stable at very steep angle owing to the matric suction (negative pore pressure) which adds to the shear strength of the soil[14]. During the rainfall when the water infiltrates the soil it decreases the matric suction, increase the pore water pressure, and decrease the shear strength which leads to the failure of slope. Therefore, the conventional slope stability analysis based on saturated condition is not appropriate for residual soil slopes [15, 16], and hydraulic properties of unsaturated soil must be incorporated in the slope stability assessment.

The hydraulic properties of the residual soil in the unsaturated zone play an important role in the hydraulic response of the soil. The hydraulic properties of the unsaturated soil are governed by soil water characteristic curve (SWCC) and hydraulic conductivity function. The SWCC illustrates the capacity of soil to retain water at different suctions. The relation between matric suction and water content in the soil can be measured in the laboratory and data obtained can be plotted using mathematical expression with curves that fit the data points [17]. such kind of equations have been proposed by various researchers [18-20]. In this study the well-known and widely adopted model in the literature proposed by van Genuchten [19] as expressed in Eq. (1) was used.

$$S(\psi) = S_{res} + (S_{sat} - S_{res})\left[1+\left(g_a\,|\psi|\right)^{g_n}\right]^{gc} \qquad (1)$$

Where S_{res} is saturation that remains at high matric suction, S_{sat} is degree of saturation at complete saturated condition, g_a, g_n and g_c are curve fitting parameters.

The hydraulic conductivity in unsaturated zone depends on saturation degree of the soil. The ratio of hydraulic conductivity at a given saturation to the hydraulic conductivity at saturation is called as relative hydraulic conductivity which can be expressed as:

$$k_r = \frac{k}{k_{sat}} \rightarrow k = k_{sat} \times k_r \qquad (2)$$

According to van Genuchten-mualem model [19, 21], the relative hydraulic conductivity is related to saturation via effective saturation as expressed in Eq. (3):

$$k_r = S_{eff}^{\;g_l}\left[1-\left\{1-S_{eff}^{\left(\frac{g_n}{g_n-1}\right)}\right\}^{\left(\frac{g_n-1}{gn}\right)}\right]^2 \qquad (3)$$

Where S_{eff} is effective saturation and g_l is pore connectivity parameter. Thus, the hydraulic conductivity of the soil at any given saturation can be calculated as

$$k(s) = k_{sat} \times S_{eff}^{\;g_l}\left[1-\left\{1-S_{eff}^{\left(\frac{g_n}{g_n-1}\right)}\right\}^{\left(\frac{g_n-1}{gn}\right)}\right]^2 \qquad (4)$$

Similarly shear strength parameters, such as cohesion and angle of internal frictions are important for any slope stability assessment. The shear strength of soil comes from two components, angle of internal fraction φ' and cohesion c' and can be expressed as:

$$T_f = c' + \sigma' \operatorname{Tan}\phi' \qquad (5)$$

Where T_f is the shear stress at failure, σ' is the effective normal stress, c' is the effective cohesion, and ϕ' is the angle of internal fraction. For unsaturated soil a generalized form of effective stress was proposed by [22, 23] which facilitates smooth transition between saturated and unsaturated states [24]:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (6)$$

Where $(u_a - u_w)$ is the matric suction, $(\sigma - u_a)$ is net normal stress, χ is soil parameter with a value 1 for full saturation and 0 for dry soil. For unsaturated soils Eq. (6) is substituted in Eq. (5):

$$T_f = c' + (\sigma - u_a)\text{Tan}\,\phi' + \chi(u_a - u_w)\text{Tan}\,\phi' \quad (7)$$

Equation (7) is the extended Mohr-Columb failure criterion suggested by [25] which relates the shear strength to the effective saturation of the soil. When soil is saturated Eq. (7) is equivalent to Eq. (5).

4. METHODOLOGY

4.1 Characterization of Residual Soil

The soil samples used in this study were collected from a slope inside UTM Johor Bahru. The top cover of vegetation was removed using the excavator and disturbed soil samples were collected. Laboratory tests were carried out on disturbed samples at Geotechnical Laboratory, School of Civil Engineering, UTM.

Various index properties tests were performed to identify basic physical properties of the soil. these tests include particle size distribution (PSD), Atterberg's limits and specific gravity which are performed According to [26-28].

Compaction test (Standard proctor) [29]was conducted on soil samples to determine the maxium dry unit weight and optimum moisture content of the soil. Different proportion of water was added to the soil samples, and the samples were kept in ceiling bags for 24 hours to ensure proper moisture absorption before the test.

The shear strength properties were determined in the laboratory using unconfined compressive strength [30], unconsolidated undrained test (UU) [31]and isotopically undrained triaxial test (CIU) [32] with pore pressure measurements. The remolded samples having 38 mm diameter and 76 mm height were compacted at maximum dry density.

Falling head Permeability tests [33] were performed to determine the saturated hydraulic conductivity of the soil. The sample was compacted in a mould and kept for saturation in the water for 24 hours. The time for 20 cm drop in head were recorded. The tests were repeated 6 times for each sample and the average reading of each trial was taken. After the completion of the hydraulic conductivity test, a representative sample was taken from the mould and kept in the oven to find the saturated water content (Gravimetric water content) of the soil.

Soil water characteristic curve was obtained using the pressure plate extractor according to ASTM [34]. The SWCC is determined using pressure plate at the applied suction of 10,20,30,50,100,200,400 and 800 kPa.

4.2 Slope Stability Analysis

4.2.1 Slope geometry and boundary condition

To study the effect of rainfall on the slope and check the stability of the slope subjected to rainfall, a typical slope profile with height (H) of 8 meter and angle of 45 was simulated using 2D FEM software PLAXIS [35]. The 1H:1V slope is selected because it is considered stable in residual soil [36]. The slope geometry as shown in Fig.1 was constructed as suggested by [37].

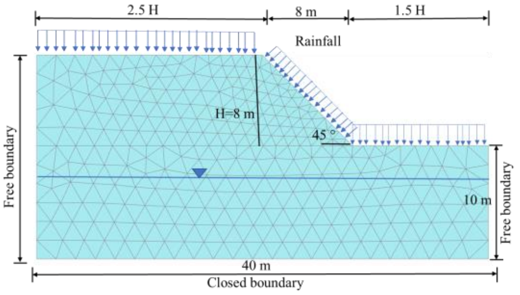

Fig.1: Slope profile and boundary conditions

A rainfall event of 364 mm was selected to study the effect of rainfall on the stability of slope. The total rainfall was distributed into 8 different rainfall intensity and duration as shown in table 1. The 80 mm/hr intensity of rainfall was adopted as it is considered as the greatest rainfall intensity in the world [38]. While the other 7 rainfall intensities were taken as a multiplicative function of the saturated hydraulic conductivity of the soil.

Table 1 Rainfall intensities and duration adopted in the study

No	Intensity (mm/hr)	Duration (hours)
96 Ks	80	4.55
20 Ks	16.6	21.9
10 Ks	8.3	43.85
8 Ks	6.64	54.81
4 Ks	3.32	109.63
2 Ks	1.66	219.27
1.5 Ks	1.24	293.54
1 Ks	0.83	438.55

A two-dimensional plain strain model was adopted in this study. The boundary conditions and finite element mesh are shown in Fig.1. The right and left side boundary was assigned as free boundary, while the bottom boundary was considered as impervious layer. A constant precipitation of different magnitude (as shown in table 1) was applied on the top boundary of the slope. The minimum and maximum pore pressure head are set as -1.0 m and 0.1 m, respectively. Which means water will run off if the water rises to 0.1 m above the ground, and evaporation will start if the ground surface become unsaturated up to depth -1.0 m.

4.2.2 Initial condition

The initial stress generation within the slope was done using the gravity loading function of PLAXIS for nonhorizontal layers. The initial ground water table was considered at 10 m below the ground surface which is the typical ground water level in the study location [39]. The limit on the suction (30 kPa) was imposed to prevent the generation of unrealistic suction. This limit was imposed based on the field observation of suction conducted at the study location [40].

4.2.3 Fully coupled deformation analysis

After initial stress generation fully coupled deformation analysis was performed. Coupled deformation analysis can concurrently determine deformation and pore water pressure in soils due to the changing time dependent hydraulic boundary conditions. The rainfall was included by assigning precipitation based on table 1.

4.2.4 Safety analysis:

Each couple deformation analysis is followed by safety analysis to evaluate the effect of rainfall on the factor of safety. Safety analysis use phi-c reduction method, which reduces the strength parameters c` and phi of the soil until the failure occurs.

5. RESULTS & DISCUSSIONS

5.1 Characterization of the Soil

5.1.1 Index properties

A series of index property tests such as sieve analysis, Atterberg’s limits and specific gravity were conducted on the soil samples. The results of Particle size distribution (PSD) and liquid limits can be used to classify the soil and to estimate the soil water characteristic curve (SWCC). The particle size distribution of the soil is shown in Fig.2 which is combination of wet sieving, dry sieving, and hydrometer analysis. For fraction passing 0.075 mm hydrometer analysis was used. The percentage of gravel, sand, silt, and clay is 6%,29%,35 %, and 30 % respectively.

The soil Atterberg’s limits were determined to understand the consistency of the soil. The liquid limit, plastic limit and plasticity index of the soil were found to be 76%, 42% and 34% respectively. The higher liquid limit is due to the high fraction of soil passing through 75 µm, which is 65%.

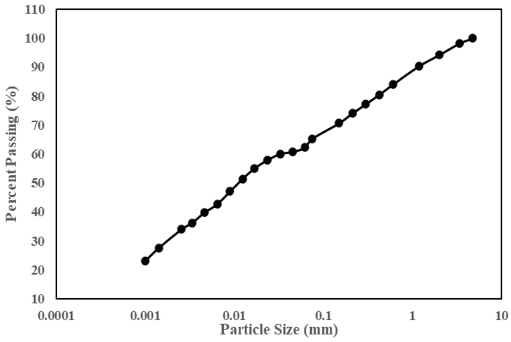

Fig.2 Particle size distribution of the residual soil

The soil can be classified as high plasticity silt (MH) according to Unified Soil Classification System (USCS). The specific gravity based on pycnometer test is 2.64. The summary of the index properties is given in table 2 below.

Table 2 Summary of the index properties

Composition	Value
Natural moisture content %	32
% Passing 75 µm	65
Liquid limit %	76
Plastic limit %	42
Plasticity Index %	34
Soil classification	High plasticity silt (MH)
Specific gravity	2.64

5.1.2 Compaction characteristics:

Compaction curve obtained from proctor test on the soil sample is shown in the Fig.3. The maxium dry unit weight and optimum moisture content is 13.2 KN/m^3 and 30% respectively.

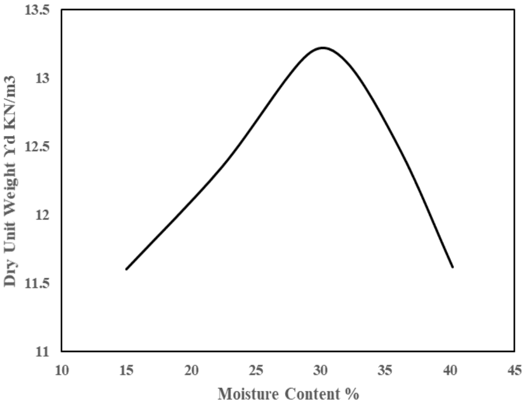

Fig.3 Compaction curve of the soil

5.1.3 Coefficient of saturated hydraulic conductivity (Ks):

Hydraulic conductivity is important parameters in the context of slope stability assessment. Falling head permeability tests were conducted on soil samples to find the coefficient of saturated hydraulic conductivity. The Ks based on falling head method was found to be 2.32 E-7 m/s confirming the fine-grained nature of the soil.

5.1.4 Shear Strength parameters:

Unconfined compressive strength, unconsolidated undrained test and consolidated undrained test with pore pressure measurements were conducted to find the total and effective shear strength parameters of the soil. The average unconfined compressive strength for this study was found to be 43 kPa. The average undrained shear strength (S_u) based on the unconsolidated drained test under cell pressure of 50, 100 and 200 kPa was 105 kPa. The results of consolidated undrained test show that the value of effective cohesion and effective angle of internal fraction is 8 and 32°, respectively.

5.1.5 Soil Water Characteristic Curve:

The SWCC known as retention curve is an important parameter in term of unsaturated slope stability assessment. The SWCC is determined using pressure plate at the applied suction of 10,20,30,50,100,200,400 and 800 kPa. As the field suction value in the study location is 30 kPa in the driest season [40] and can rarely go beyond 800 kPa. Therefore, the SWCC was determined in the above-mentioned range only. After each application of suction, the saturated gravimetric water content was determined. As PLAXIS requires SWCC in terms of degree of saturation, the gravimetric water content was converted to degree of saturation using Eq. (8) below:

$$S = \frac{wG_s}{e} \tag{8}$$

To obtain the curve fitting parameters the experimental data was fitted to Ven Genutchen model Eq. (1) using a least square regression method[14]. This can be done using a spread sheet. While carrying out the best fit regression analysis, an initial reasonable value for the curve fitting parameters g_a and g_n must be selected. Then the following objective function (sum of the square residual) which can be minimized with respect to $g_a$and g_n.

$$O(g_a, g_n) = \Sigma_i^N \left[\theta_i - \theta\left(g_a - g_n\right)\right]^2 \tag{9}$$

Where $O(g_a, g_n)$ is objective function, N is the number of measurements and θ_i are measured values. Fig.4 shows the SWCC and curve fitting parameters of the soil.

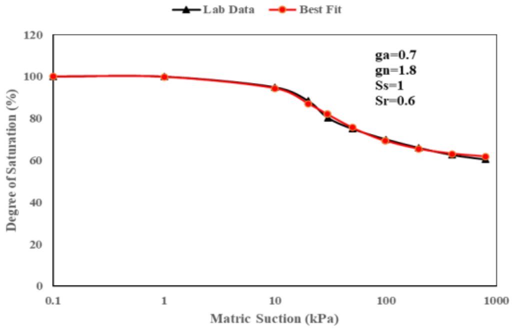

Fig. 4 SWCC of the soil

5.2 Slope Stability Analysis

To study the effect of rainfall on the safety factor of the slope, unsaturated slope stability using phi c reduction method was performed. Two sets of rainfall event, short duration and high intensity rainfall, low intensity and long duration rainfall were considered to analyze the effect of extreme rainfall events on slope stability. Stress points at different depth (0.5,1,2,3,3.5 m) from the slope crest were selected to study the matric suction in response to different intensity and duration rainfall events. The summary of properties used in the numerical model is listed in table 3.

Table 3 Soil properties used in the model

Properties	Values
Unit weight γ_{unsat} (KN/m$^{3)}$	13.2
Young modulus E' (KN/m^2)	10000
Poisson's Ratio v'	0.33
Effective cohesion c' (KN/m^2)	8
Effective friction angle ϕ'	32°
hydraulic conductivity K_s (m/s)	2.32 E-7
Residual Saturation S_{res}	0.6
Complete saturation S_{sat}	1
g_a	0.7
g_n	1.8
g_l	0.5

5.2.1 Short duration high intensity rainfall

Fig. 5 shows the change in factor of safety in the response of the short duration high intensity rainfall (I≥ 8Ks). The initial factor of safety (FOS) of the slope before any simulated rainfall was found to be 2.02. It is evident that the high intensity rainfall has a less significant effect on the stability of the slope with a minimum safety factor of 1.95 at rainfall intensity of I=8Ks. While Rainfall of intensity, I=96

Ks, I=20 Ks, I=10 Ks resulted in FOS of 2.01, 2.0, and 1.98 respectively.

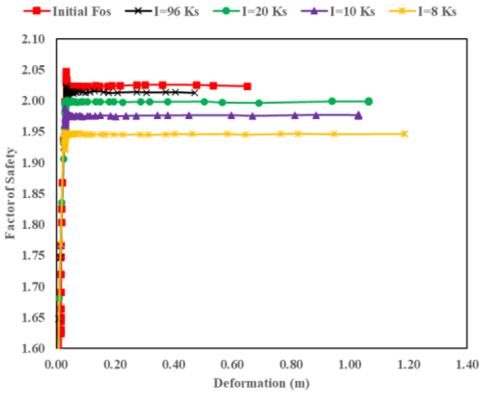

Fig.5 Factor of safety for high intensity short duration rainfall

The less significant effect of high intensity short duration rainfall is because, the intensity of the rainfall events is very high compared to the saturated hydraulic conductivity of the soil at the initial suction of 30 kPa. This low hydraulic conductivity of the soil resulted in minimum infiltration of the rainwater into the slope, while most of the rainfall water contributes to the surface runoff and results in shallow saturation. This can be confirmed from the matric suction response of the soil inside the slope as shown in Fig.6a and Fig.6b. Fig.6 (a) shows the suction response of soil at 0.5 m below the crest of the slope for high intensity rainfall. The soil at 0.5 meter reaches saturation for the rainfall intensity for 8 Ks only, while the infiltrated water for rainfall intensity of I=96 Ks, I=20 Ks and I=10 Ks is not sufficent enough to saturated the soil. As the depth increase further to 1 m (Fig.7b) the effect of rainfall on the matric suction becomes negligible. As a result there is no significant reduction in shear strenth of the soil which leads to higher FOS.

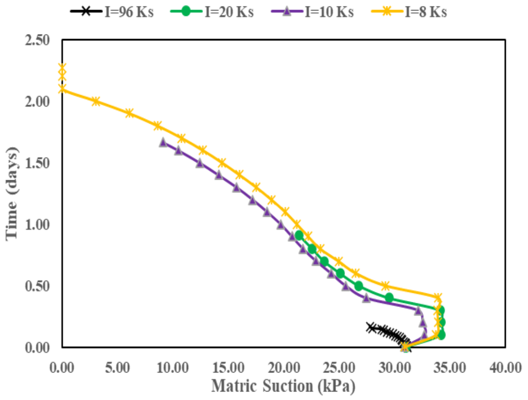

Fig.6a Matric suction response at depth 0.5 m

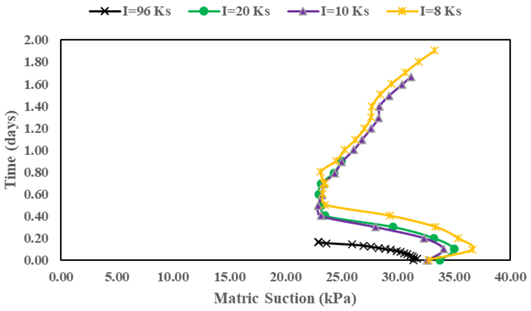

Fig.6b Matric suction response at depth 1 m

5.2.2 Long duration low intensity rainfall

Fig.7 shows the FOS for long duration low intensity rainfall (I≤ 4Ks). The low intensity rainfall decreases the factor of safety significantly. The rate and magnitude of the decrease in the safety factor is related to the intensity and duration of the rainfall.

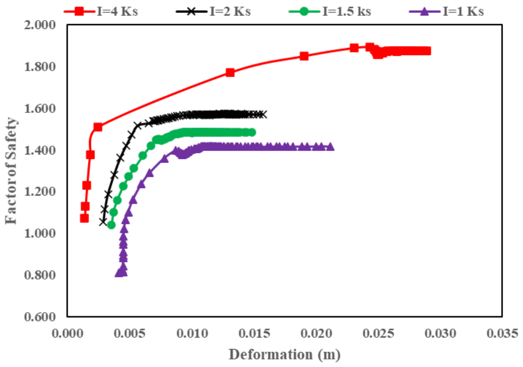

Fig.7 Factor of safety for low intensity long duration rainfall

The low factor of safety for long duration low intensity rainfall can be attributed to the fact that low intensity rainfall results in deeper saturation and significantly reduced the matric suction of the soil. As the presence of matric suction in unsaturated soil increase the shear strength, this reduction in the matric suction leads to decreased shear strength of the soil which results in lower FOS. During the prolonged duration of rainfall, the quantity of infiltrated rainwater is sufficient to advance the wetting front to the depth of 3.5 m. The rainfall of intensity I≤4 Ks resulted in a deeper wetting front leading to diminished suction value of 0 at depth 3.5 for rainfall intensity of 1=1 Ks as shown in Fig.8d. The deeper saturation resulting in a minimum FOS of 1.41 with a change in FOS of 29.85 %. It is worth noting that for rainfall intensity of 1.5-4 Ks the advancing wetting font reached a depth of a maximum of 2 m below the surface as shown in Fig.8b. Beyond 2m depth (Fig.8c & Fig.8d), the infiltrated rainwater is not enough to advance the wetting font further and bring the soil to saturation. The change in the FOS for different rainfall intensities is listed in table 4.

Table 4 Percent change in FOS for different intensity rainfall

Rainfall Intensity	Initial FOS	Final FOS	% Change
96 Ks	2.01	2.01	0
20 Ks	2.01	1.99	1
10 Ks	2.01	1.97	2
8 Ks	2.01	1.94	3.4
4 Ks	2.01	1.87	6.96
2 Ks	2.01	1.57	21.9
1.5 Ks	2.01	1.48	26.36
1 Ks	2.01	1.41	29.85

In general, the change in matric suction due to rainfall decreases with depth. It depends on the saturated hydraulic conductivity (Ks), intensity, and duration of the applied rainfall. For low Ks and fine-grained soil as used in this study, the longer duration low-intensity rainfall results in deeper saturation than the higher intensity and short duration rainfall, thus resulting in lower FOS. When a rainfall of intensity greater than the Ks of the soil is applied on the slope, most of the rainwater will contribute to surface runoff, and less quantity of rain will infiltrate the soil. This results in minimum change in matric suction response and less significant effect on the FOS of the slopes.

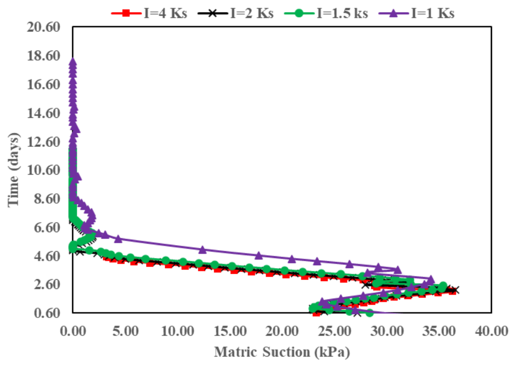

Fig.8a Matric suction response at depth 1 meter

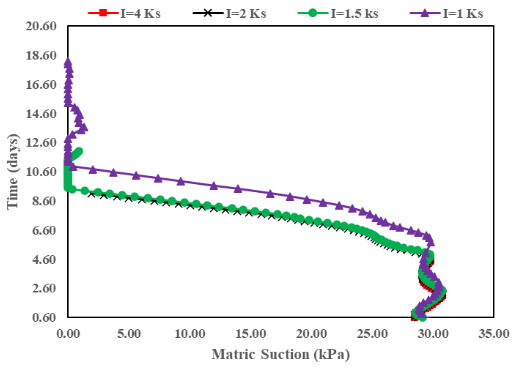

Figure .8b Matric suction response at depth 2 meter

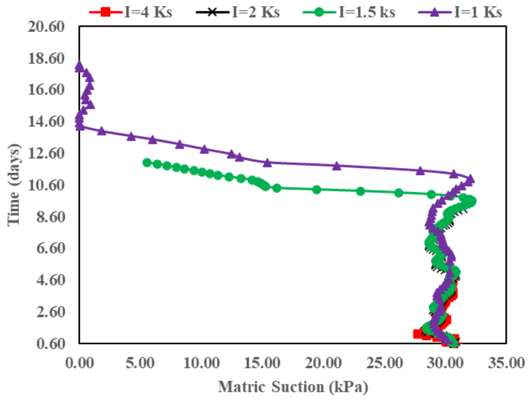

Fig.8c Matric suction response at depth 3

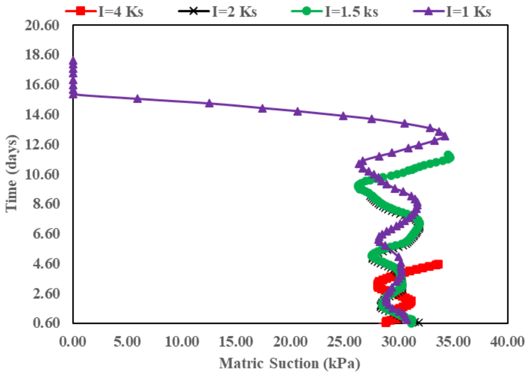

Fig.8d Matric suction response at depth 3.5 meter

6. CONCLUSION

The properties of residual soil sample for a tropical region have been assessed in this study. The common engineering and index properties of residual soil have been investigated with special focus on properties which can be used in the slope stability assessment. The lab results based on particle size distribution and consistency limits revealed that the soil is fine-grained and can be classified as high plasticity silt (MH) according to unified soil classification system. The max dry unit weight and optimum moisture content is 13.17 kN/m3 and 30 % respectively. The shear strength parameter, angle of internal friction and cohesion is 32° and 8 kPa respectively, while the unconsolidated undrained shear strength and unconfined compressive strength of the soil is 105 kPa and 43 kPa, respectively. The hydraulic conductivity and saturated gravimetric water content are 2.32 x 10-7 m/s and 54%, which confirm the fine-grained nature of the soil. Based on these results the stability of slopes under different intensity and duration of rainfall was investigated using PLAXIS. The slope stability analysis shows that due to the fine-grained nature of the soil the slopes in the study area are more critical to low intensity long duration rainfall (I≤ 4Ks). High intensity and short duration rainfall have no significant effect on the stability of the slopes because the Ks of the soil is way smaller than the rainfall intensities of all 4 simulated rainfall events. as most of the rainwater contribute to runoff and less water infiltrate into the soil. The results found in this study contribute to the existing literature on residual soil properties with special focus on properties which are important to slope related problem. These results can be used in preliminary slope stability assessment, numerical modelling of the slope and slope stability related problems. In this study limited soil properties with limited soil samples were assessed. For in depth slope stability analysis large number of samples can assessed for various soil properties. In addition, samples from different geographical locations can be evaluated for this purpose.

7. ACKNOWLEDGMENTS

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