Establishment of Fundamental Characteristics of Unsaturated Sri Lankan Residual Soils.

Nanthini Vasanthan
Geotechnical Engineering Division, National Building Research Organisation

Nirmanthi Idirimanna
Landslide Research & Risk Management Division, National Building Research Organisation

Prof. S.A.S.Kulathilaka
Civil Engineering Department, University of Moratuwa, Sri Lanka

ABSTRACT: Slope failure in tropical climates frequently occurs due to excessive rainfall. Heavy infiltration cause destruction of matric suctions, development of perched water table conditions and rise of ground water table. Severe erosion and surface destruction will also be caused by the heavy prolonged rainfall. In order to understand the threshold values of rainfall leading to instability it is necessary to model this process with a reasonable accuracy. Sri Lankan residual soil formations are formed by weathering of the metamorphic parent rock and have inherited significant abrupt variations in engineering characteristics. Basic characteristics of these soil formations such as Soil Water Characteristic Curves (SWCC), Variation of permeability with water content and unsaturated shear strength parameters are essential parameters in these analyses. These characteristics have not been established for typical residual soils forming slopes in Sri Lanka.

This paper highlights the need for detailed experimental studies and presents preliminary studies that have been conducted at the NBRO laboratories to establish the characteristics of unsaturated Sri Lankan residual soils. Undisturbed samples of soil obtained from the failed slope at Welipenna in the Southern Expressway were used in this study. Direct shear tests were done by modifying the conventional apparatus by incorporating a miniature tensiometer which allows for the simple and direct measurement of soil matric suction during shearing. Soil water characteristic curves (SWCC) were also established using these apparatus. Alternatively, pressure plate apparatus was also used for this purpose.

Permeability function for both wetting and drying phases were also investigated on undisturbed samples. The method is based on continuously drying and wetting the soil sample while continuously monitoring the suction gradient and the change in soil mass. The paper highlights the importance of these studies and presents the procedures that are being used. Some results obtained at this preliminary stage are also presented.

1. BACKGROUND

Landslides in Sri Lanka and in many tropical countries are triggered by excessive rainfall. Rain induced failures in slopes made of residual soils are a major geotechnical hazards in Sri Lanka. These soils which are formed by the in-situ weathering of the metamorphic parent rock are characterized by the heterogeneous nature inherited from the difference in its mineralogy and the process of variable weathering under tropical conditions. Safety margins of these slopes are high during the periods of dry weather due the prevailing matric suctions. Rainwater infiltration causes loss of matric suction, development of perched water table conditions and rise of ground water table. Zones of contrasting permeability due to heterogeneous nature discussed above leads to build up of pore pressures at those boundaries. (Kulathilaka and Sujeevan, 2011). The systems of joints in the parent rock remain as zones of weak and high permeability in the residual soil formed. They are termed as relict joints and are zones of special importance in the modelling process.

Many researchers in the region have studied the effects of rainfall on the pore pressure regime by both analytical and experimental approaches. Rahardjo et.al., (2000), studied the process through an instrumented slope at the Nanyang Technological University in Singapore. Similar studies were done by Jotisankasa et al., (2008) in Thailand.

Soil Water Characteristic Curve (SWCC) defining the variation of matric suction with volumetric water content (Fig. 1) and Permeability function defining the variation of permeability with the matric suction are essential characteristics to be used in the modeling of the infiltration process. An idealized SWCC shows two characteristic points A* and B*. Point A* corresponds to the air-entry value ($(u_a-u_w)_b$), and B* corresponds to the residual water content (θ_r). As shown in Fig. 1, prior to A*, the soil is saturated or nearly saturated, so it can be treated as a saturated. Beyond B*, there is little water in the soil, so the effects of water content or negative pore-water pressure on soil behaviour may be negligible.

What is of great concern in an unsaturated soils is the stage between A* and B*, in which both air and water phases are continuous or partially continuous, and hence the soil properties are strongly related to its water content or negative pore-water pressure.

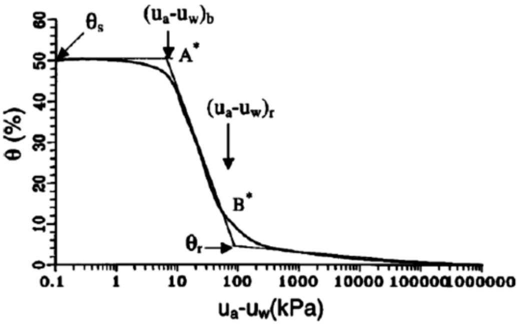


Fig. 1: An idealized soil water characteristic curve

2. ANALYTICAL STUDIES DONE IN SRI LANKA

Sujeevan and Kulathilaka (2011) modeled the infiltration into a typical cut slope in the Southern Expressway using Geo-slope SEEP/W software. Results of studies on cut slopes with a gradient of 1:1 with 2m wide berms at vertical intervals of 7.5 are presented here. The geometry of the cut slope and the boundary conditions utilized for the transient seepage analysis are shown in Fig. 2. Three cases of sub soil condition were studied. In Case 1 the entire slope is assumed to be made of residual soils and in Case 2 a thick layer of residual soil is underlain by weathered rock. The boundary between the residual soil and the weathered rock is shown by line JC in Fig. 2. Finally in the Case 3 the thickness of the residual soil is much lower and the boundary between the residual soil and the weathered rock is shown by line IC in Fig. 2. A boundary flux, *q*, equal to the desired rainfall intensity, *Ir*, was applied to the surface of the slope. The nodal flux, *Q*, was taken to be zero at the sides of the slope above the water table and at the bottom of the slope to simulate a no flow zone (Fig. 2). Equal total heads, *ht*, were applied at the sides of the slope below the water table. The broken line indicates the initial water table of the slopes and it was taken to be the same for all three cases. Analysis was carried out for different rainfall intensities such as of 5mm/hr, 20mm/hr over duration of 1 to 5 days. In the absence of actual Soil Water Characteristic Curves and Permeability functions of different soil layers some standard data available in literature was used (Fig. 3).

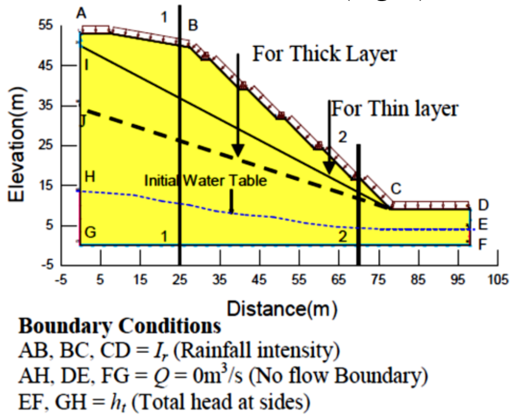


Fig. 2: Cut slope (1:1) geometry, selected sections and boundary conditions

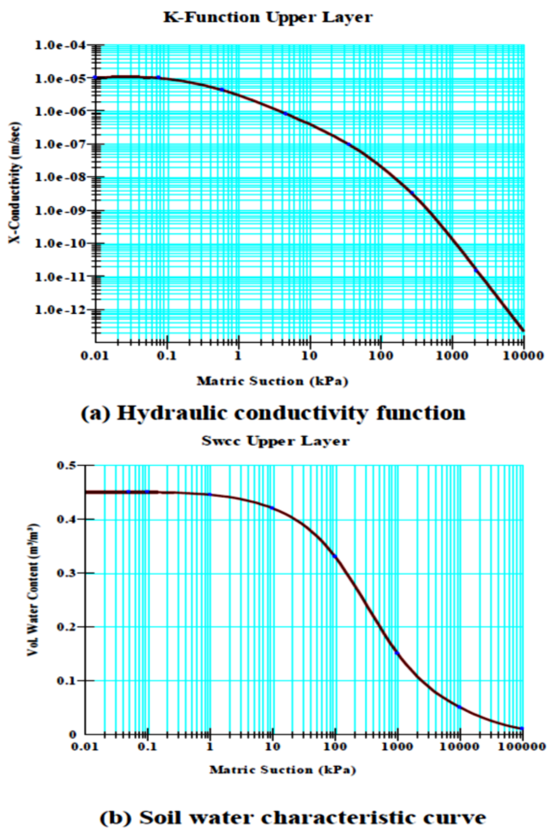
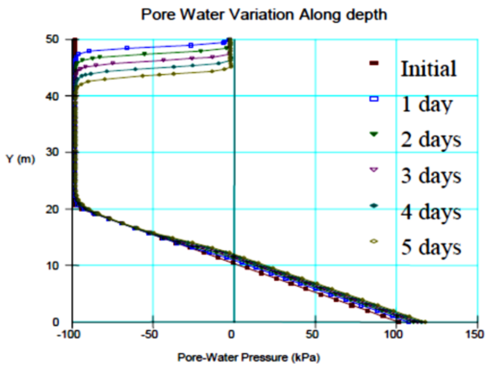


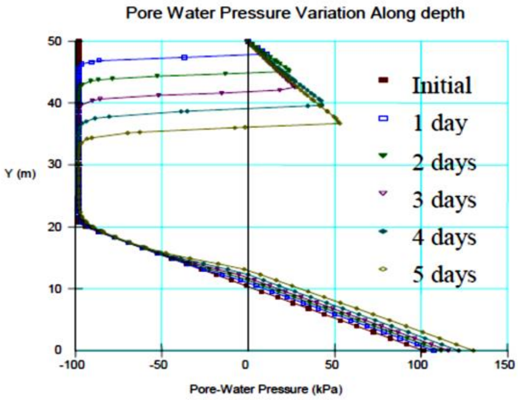
Fig. 3: Characteristics of residual soils used

Initial pore water pressure profile was assigned with an upper limit of 100 kN/m^2 on the matric suction. The variation of pore pressure over the depth due to the prolonged rainfall was studied. Fig. 4 presents the variations in the pore pressure regime at Section 1 for a rainfall of intensity 5mm/hr. It could be seen that the matric suction is completely lost over a depth of around 5m and there is a very small rise of ground water table. When the rainfall intensity is 20 mm/hr, a perched water table condition has developed at Section 1 (Fig. 5). The ground water table rise is not very significant. At section 2 there is a perched water table at the initial stages and a significant rise of ground water table (Fig. 6).



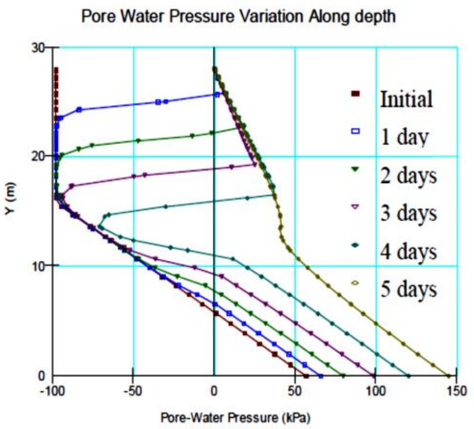
(a) For Section 1-1

Fig. 4: Variation of pore water pressure for rainfall of 5mm/hr (after Sujeevan and Kulathilaka, 2011)



(a) For Section 1-1

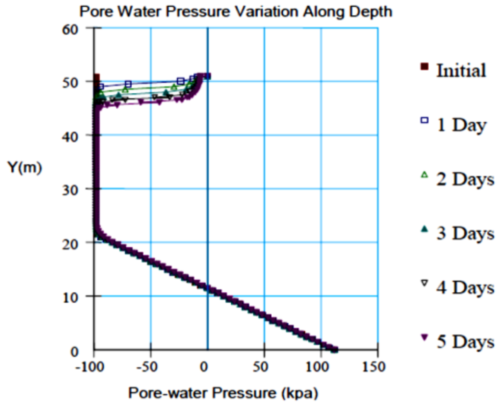
Fig. 5: Variation of pore water pressure for rainfall of 20mm/hr (after Sujeevan and Kulathilaka, 2011)



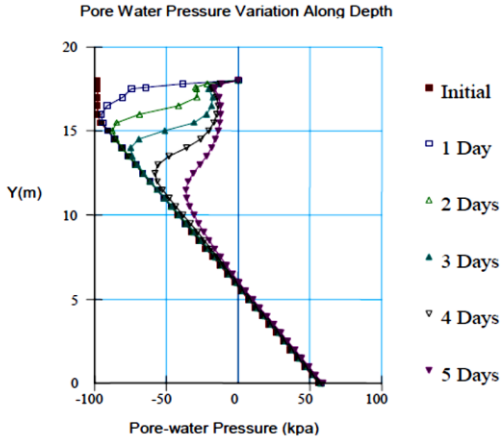
(b) For Section 2-2

Fig. 6: Variation of pore water pressure for rainfall of 20mm/hr (after Sujeevan and Kulathilaka, 2011)

If there are surface drainage measures and surface protection vegetation of lower permeability (10^{-7} m/s) the infiltration would be much reduced as illustrated in Fig. 7. (Kulathilaka and Kumara, 2011).



(a) For Section 1-1



(b) For Section 2-2

Fig. 7: Pore water pressure distribution for 5mm/hr rainfall with vegetation layer of permeability 10^{-7}m/s (Case 1) (after Kulathilaka and Kumara, 2011)

3. NEED FOR EVALUATION OF UNSATURATED CHARACTERISTICS

The preceding sections illustrated the mechanism of infiltration and changes made in the pore pressure regime due to a prolonged rainfall. The effectiveness of the appropriate surface drainage measures and surface protecting vegetation in minimising the infiltration was also illustrated. All these results were obtained with soil characteristics available in literature and it is essential now to use actual characteristics of residual soils forming Sri Lankan slopes. This research project focuses on the evaluation of the basic unsaturated characteristics of selected Sri Lankan residual soils. Undisturbed samples obtained from the slope failure at Welipenna in the Southern Expressway were used in the study.

4. MATRIC SUCTION MEASUREMENT

In a soil formation containing fine grained soils some water is retained due to capillary actions and pore water pressure would be less than atmospheric (negative). This negative pore water pressure, or the tensile stress in soil water, is also referred as the matric suction, s,

$$s = u_a - u_w \quad (1)$$

Where u_a is the pore air pressure (equal to zero at atmospheric condition) and u_w is the pore water pressure. There are varieties of methods for measurement of matric suction such as axis-translation, tensiometer, filter paper etc. (Fredlund & Rahardjo, 1993).

In this research project a miniature tensiometer developed consisting of MEMs pressure sensor, 1Bar High-Air-Entry porous ceramic and transparent acrylic tube at the Kasetsart University (KU), Thailand is used (Fig. 8). The device requires thorough saturation with water so that tensile stress can be transferred effectively between the soil water and the pressure sensor. This is normally achieved by evacuating air from different parts of the device in a water-filled reservoir using a vacuum pump, as described in details by Jotisankasa (2010).

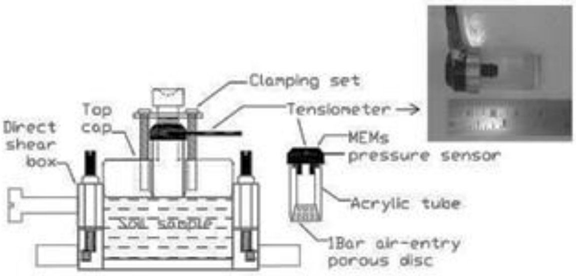


Fig. 8: KU-tensiometer and its incorporation in direct shear box (modified from Jotisankasa and Mairaing, 2010).

The major advantage of using the KU-tensiometer for measurement of soil wetness in slope studies is that the device can also be used as piezometer to monitor positive pore water pressure as in traditional geotechnical engineering practice.

5. DETERMINATION OF SHEAR STRENGH OF UNSATURATED SOILS

The shear strength of an unsaturated soil can be expressed as;

$$\tau = c' + (\sigma - u_a)\tan\phi' + c^s \quad (2)$$

Where,

c' = Effective cohesion intercept,

σ = Normal total stress,

u_a = pore air pressure (for atmospheric pressure, u_a equals zero),

ϕ'= the effective angle of shearing resistance, and

c^s = the additional cohesion in unsaturated soil due to matric suction.

The value of c^s can be determined as follows;

$$c^s = (u_a - u_w)\tan\phi^b \text{, if } u_w < u_a \quad (3)$$

Where,

u_w = pore water pressure,

ϕ^b = angle of shearing resistance due to suction.

Jotisankasa & Mairaing (2010) studied the relationship between c^s and suction of residual soils from landslide areas using the suction-monitored direct shear test presented in Figure 8. Only minor modification was made to the top cap of conventional direct shear box, whereby the tensiometer is inserted through an orifice of the top cap and a clamping set was used to secure the tensiometer in place during shearing. The main difference is that the miniature tensiometer used in this study was of a lower capacity, capable of measuring suction from value of zero to 100kPa. This smaller range of suction is however more appropriate for slope stability studies.

During testing, a constant water content condition of the soil specimen can be maintained by using plastic wrap and pieces of wet clothes to cover the whole shear box. Typical testing program for characterization of soils in slope stability studies consists of slow (consolidated-drained) shearing tests on saturated samples and constant-water-content shearing tests on unsaturated samples with various initial suctions. In unsaturated tests, the moisture content samples can be modified to the required values prior to testing by either gradual water spraying or air-drying.

Such suction-monitored shearing tests thus offer alternative tools for characterizing unsaturated shear strength in slope stability studies. It is also appreciated that the failure condition in the soil slope during rainfall could be simulated by the shearing infiltration test with increasing pore water pressure and constant total stress (Rahardjo et al., 2009). For practical purpose, the conventional suction-monitored shearing tests can be used in this study and will be adequate for the first estimate. Further research is still needed to investigate whether or not the shear strength parameters (i.e.ϕ', c', c^s, ϕ^b) from conventional shear tests and shearing infiltration test are essentially the same.

6. ESTABLISHMENT OF SOIL WATER CHARACTERITIC CURVE

An idealized Soil Water Characteristic Curve is presented in Fig. 1. The soil-water characteristic curve for a soil is defined as the relationship between water content (soil wetness) and suction for the soil. The Soil-Water Characteristic Curve (SWCC) is also called the Soil-Water Retention Curve. The water content defines the amount of water contained within the pores of the soil. In soil science, volumetric water content θ is most commonly used. In geotechnical engineering practice, gravimetric water content, is the most commonly used parameter. The suction may be either the matric suction of the soil or total suction (i.e., matric plus osmotic suction).

Degree of saturation, S_r, gravimetric water content, w, or volumetric water content, θ, are all related by the equation,

$$\theta = wG_s/(1+e) = S_r e/(1+e) \quad (4)$$

As already outlined SWCC is required as a key property for advanced analysis of slope including infiltration, and prediction of unsaturated shear strength. As illustrated by equations 2 and 3 the shear strength of an unsaturated soil is related to the prevailing matric suction.

Jotisankasa & Vathananukij (2008) made use of the SWCC to estimate the amount of rainfall required to reduce the suction to zero or saturate the slope. This was to be used as basis for early warning system for shallow landslide.

Various methods such as; axis translation, filter paper, tensiometer, chilled-mirror hygrometer etc. could be used to determine the SWCC. In this study, SWCC of intact undisturbed samples was determined using miniature KU tensiometer sensor (Fig. 9) and pressure plate apparatus.

7. MEASUREMENT OF SWCC USING KU TENSIOMETER

Fig. 9: Miniature KU tensiometer sensor

The method is called continuous measurement. For the drying SWCC, the top surface of soil sample can be left exposed to ambient air, and the soil suction can be monitored continuously at three locations on sample's side as shown in Fig. 10. The weight of the sample can also be continuously measured using an electric balance connected to a data logger.

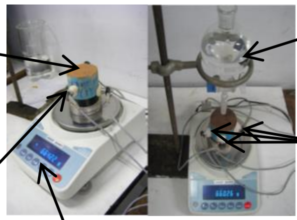


Fig. 10: Experiment setup for the continuous measurement of SWCC.

For the determination of wetting SWCC, the top surface of sample can be continuously wetted by way of water dripping from burette as shown in Fig. 10. The main advantage of the continuous SWCC measurement is the shorter testing duration which is only a few days per one path (from suction of 100 kN/m^2 to 0 kN/m^2). Besides, the function of permeability at different suctions, and water contents can also be determined from this test as described in the proceeding sections.

8. MEASUREMENT SWCC USING PRESSURE PLATE APPARATUS

Soil-water characteristic curve of a soil can be obtained by using a pressure-plate apparatus also. In this research, a 5-bar pressure plate apparatus shown in Fig. 11 was used for this purpose.

Fig. 11: Pressure plate (5-bar) extractor used in this work

The volumetric water content θ_w can be defined as follows,

$$\theta_w = V_w / V_s \quad (5)$$

V_w = Volume of water content
V_s = Volume of soil
Can be converted as follows,

$$\theta_w = w \times \rho_d / \rho_w \quad (6)$$

w = gravimetric moisture content
ρ_d = Dry density of soil
ρ_w = Density of water

9. DETERMINAION OF PERMEABILITY FUNCTION

Permeability function is one of the most sophisticated parameters to measure in unsaturated soils. The aforementioned continuous SWCC measurement method can also be used to determine the permeability function. The values of suction at three locations can be used to calculate the hydraulic gradient, i, as follows;

$$i = d\,(z - s/\gamma_w)/\,dz \qquad (7)$$

Where z is the elevation head of each tensiometer relative to the base of sample, s is matric suction, and γ_w the unit weight of water. For the drying and wetting tests, previous research experience (Jotisankasa, A., Tapparnich, J., Booncharoenpanich, P., Hunsachainan, N. & Soralump, S., 2010) suggests that the value of hydraulic gradient, i, calculated over only the upper and middle pore pressure measurement gives a better results of k-function than calculated over three measurements. This is perhaps due to non-uniformity of the pore water pressure distribution as described previously.

The plot of change in soil mass with time can be used to calculate the flux or discharge velocity, v, at any particular time as follows;

$$v = dV_w/\,Adt \qquad (8)$$

Where dV_w is the change of volume of water in soil sample which can be calculated from change in soil mass during test, *A* is the cross section area of sample, and *dt* is the elapsed time. Linear regression can be used to calculate the slope (velocity) from data points. The value of permeability at any suction and volumetric water content can then be calculated as in Eq (9).

$$k = v/\,i \qquad (9)$$

10. EXPERIMENTAL STUDIES COMPLETED TO DATE

Experimental procedures are currently in progress to establish; Soil Water Characteristic Curves, permeability functions, shear strength parameters of the unsaturated residual soils of Sri Lanka using the methods prescribed in the preceding sections. Undisturbed soil samples obtained using the box sampling technique from the site of failed slope in Welipenna of the Southern expressway are used in this context.

Initially, the basic index properties of the soil, such as; particle size distribution, Atterberg limits, specific gravity etc. were determined. Consolidation tests and permeability tests were also conducted after saturation of the samples. The saturated permeability is required in the development of the permeability function and consolidation characteristics are necessary to determine the strain rates in direct shear tests.

10.1. *Classification of the soil*

Particle size distribution obtained using the wet sieving technique is presented in Fig. 12. Soil sample has a composition of; Gravel 16%, Sand 64%, Silt 16% and Clay 4%. Atterberg limit tests indicated that the fines are non-plastic. Therefore soil is classified as silty sand (SM). Series of specific tests were performed and average value was obtained as **2.6**.

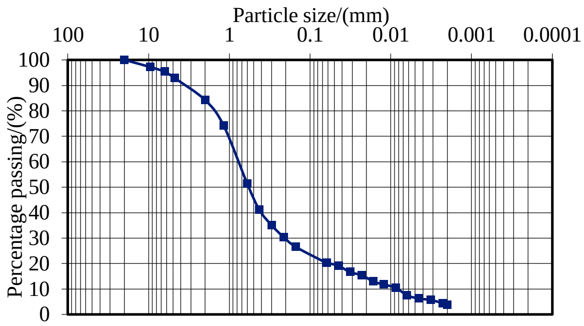
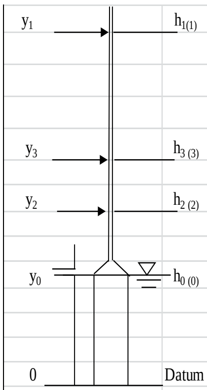


Fig. 12: Particle size distribution

10.2. *Saturated permeability of the soil*

Before developing permeability function it is necessary to find the permeability of the soil under saturated conditions and the value is **8.69x10^{-7}**m/s. The results of the test are presented in Fig. 13.



Referance point	Height above datum y (mm)		Height above outlet h (mm)		Test time t (sec)	Test time t (min)	Height ratio	
(1)	y_1	1115	h_1	932	(1 - 3) 283	4.72	h_1/h_3	2.198
(3)	y_3	607	h_3	424	(3 - 2) 315	5.25	h_3/h_2	2.197
(2)	y_2	376	h_2	193			$\log_{10}(h_1/h_3)$	0.342
(0)	y_0	183	h_0	0			$\log_{10}(h_3/h_2)$	0.342

Permeability (k) = [3.84aL log $_{10}$***(h*** $_0$***/h*** $_t$***)/At] x 10*** $^{-5}$ ***m/s***

Test run (1 to 3)	k =	0.091632	x10^{-5} m/s
Test run (3 to 2)	k =	0.082265	x10^{-5} m/s
Permeability (k) = at (25°C)		**8.69x10^{-7}**	**m/s**

Where,

L - Length of sample (mm)
A- Area of cross section of sample (mm^2)
a - Area of cross section of standpipe (mm^2)
t - Test time (min)
h_0- Drop in head at time "0"
h_t- Drop in head at time "t"

Fig. 13: Details of permeability test

10.3. *Consolidation test*

It was required to come up with an appropriate shearing rate during the testing of the samples in the direct shear box under consolidated drained conditions. Consolidation test was conducted after saturation of the samples to get an idea about the coefficient of consolidation under saturated conditions.

The variation of the coefficient of consolidation with the stress level obtained through the testing is presented in Table 1.

Table 1- Variation of coefficient of consolidation

Stress level/(kN/m^2)	Coefficient of Consolidation, /(m^2/yr)
0-50	6.6031
50-100	5.5126
100-200	3.8288

10.4. *Direct Shear Tests without suction measurements under different levels of saturation*

Direct shear test was chosen over other tests for this study because of the shorter drainage path of soil sample and thus lesser time taken to dissipate the excess pore water pressure. Test was carried out on undisturbed residual soil specimens in order to determine the shear strength parameters of soil under different levels of saturation. These tests were done as a preliminary study prior to acquiring the of KU tensiometers. The degree of saturation of test specimens was changed by adding different amount of water to natural sample. Achieved degrees of saturation were 40% (natural moisture content existed at the time collection of undisturbed sample at the site), 65%, 83% and 100%. For each degree of saturation, specimens were tested under net normal stresses of 50 kN/m^2, 100 kN/m^2, 150 kN/m^2 and 200 kN/m^2 with a shearing rate of 0.125 mm/sec. The shearing rate was estimated based on the values of coefficient of consolidation to ensure complete dissipation of pore water pressures if saturation condition has prevailed. Conditions of the test specimen are summarized in Table 2.

Table 2- Conditions of test specimen

Test number	Avg. S_r (%)	Avg. w (%)	Avg. γ_d (kg/m^3)
1(As it is)	40.20	13.36	1395.41
2	65.03	23.97	1339.89
3	82.67	32.24	1294.66
4	100.00	36.08	1369.74

Shear stress versus normal stress relationship of soil was established mathematically. The cohesion, c′ was obtained from fully saturated direct shear test and internal angle of friction, ϕ′ is taken to be constant for specific soil shown in Fig. 14. Hence, manual curve fitting was performed for the test results by keeping internal angle of friction, ϕ′ at this value to obtain relevant apparent cohesion values at different levels of saturation. The results are summarized Table 3. The variation of apparent cohesion with degree of saturation is presented in Fig. 15. As an alternate presentation the apparent cohesion is plotted against the volumetric water content in Fig. 16.

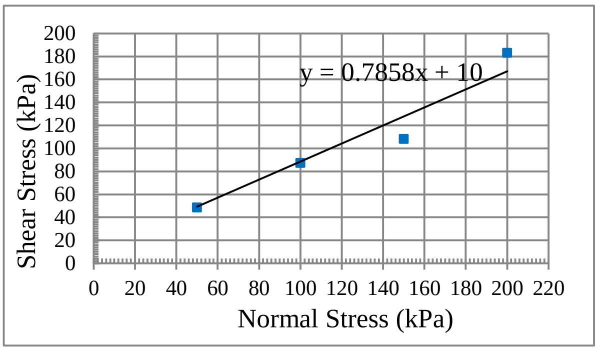


Fig. 14: The variation of shear stress with normal stress for fully saturated condition

Table 3- Apparent cohesion at different levels of saturation

Sr /(%)	Internal friction angle /(Deg.)	Apparent Cohesion /(kN/m^2)
40.20	38	42
65.03	38	38
82.67	38	30
100.00	38	10

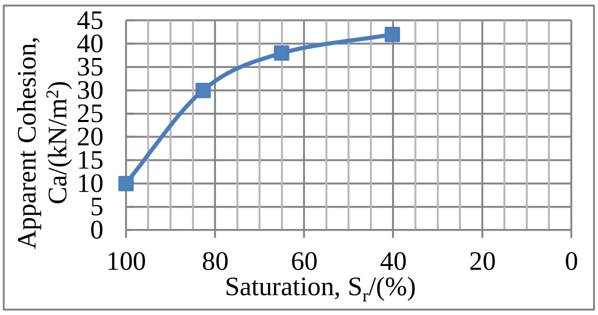


Fig. 15: The variation of apparent cohesion with degree of saturation

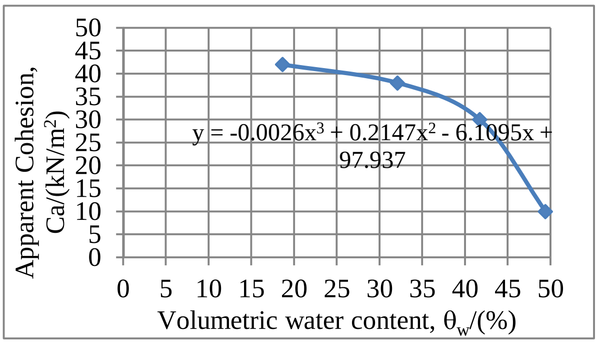


Fig. 16: The variation of apparent cohesion with percentage of volumetric water content

10.5. *Development of SWCC with Pressure plate apparatus*

The SWCC of these soil specimens was established using the pressure plate apparatus (Fig. 17). By maintaining different values of (u_a - u_w) in the apparatus for a sufficiently long period, samples were brought to equilibrium under different matric suctions. Volumetric water contents were determined by obtaining the weights of the samples under equilibrium conditions. The SWCC was developed using this process is presented in Fig. 18. The matric suction values corresponding to the water contents of the samples tested in the direct shear tests were estimated using the SWCC derived though the Pressure Plate Apparatus. The results obtained are presented in Fig. 18. Further, the variation of apparent cohesion with matric suction was developed and ϕ^b was fitted and shown in Fig. 19. However, this did not result in a linear relationship as expected. By fitting a straight line ϕ^b was obtained as approx. **13**°.

Fig. 17: Typical arrangement of pressure plate apparatus

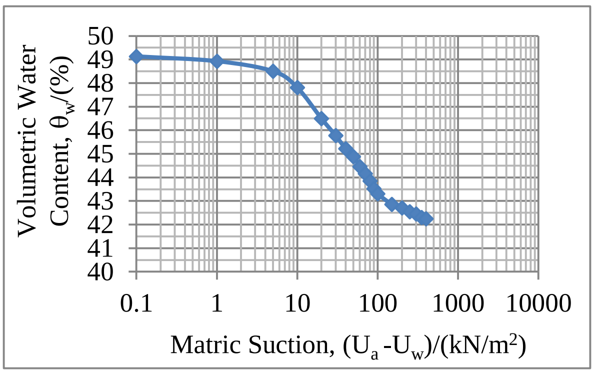


Fig. 18: The variation of percentage of volumetric water content with matric suction

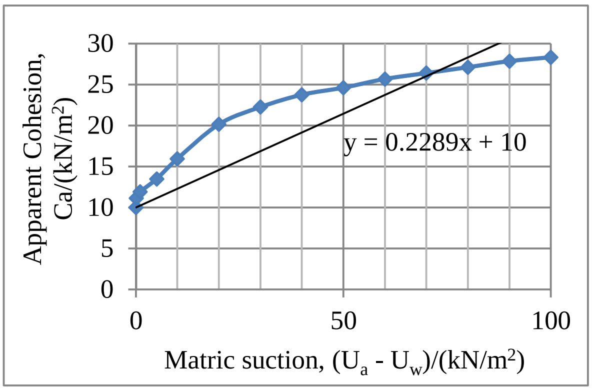


Fig. 19: The variation of apparent cohesion with matric suction

10.6. *Direct shear test with tensiometer*

After acquiring the KU-tensionmeters direct shear tests were conducted with measurement of matric suction. Ensuring the saturation of the tensiometer by complete de-airing is a tedious process which consumed a long time. As such, a complete set of results to derive the parameters could not be obtained at the time of writing this paper. The tests are now in progress after overcoming the initial difficulties. The process is illustrated in Fig. 20 & Fig. 21.

Fig. 20: Typical direct shear test with tensiometer

Fig. 21: Typical direct shear specimen after the testing

10.7. *Tests to establish permeability function*

Tests are also in progress to determine the permeability function on the drying path. The test setup used is presented in Fig. 22.

The undisturbed sample used for the permeability test was initially saturated and instrumented with three KU tensiometers at different heights on different plan locations as illustrated in Fig. 23. The rate of movement of water is very small and determined through the weight loss as determined by an electronic balance which measures to an accuracy of third decimal of a gram.

Fig. 22: Typical arrangement for drying path test

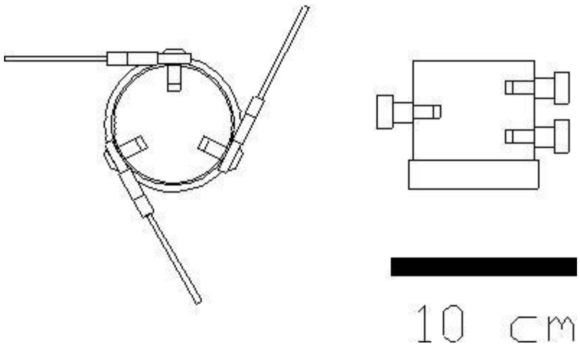


Fig. 23: Arrangement of KU-Tensiometers in permeability function for drying/wetting path test

11. CONCLUDING COMMENTS

Slope failures in tropical climates are triggered by excessive rainfall. In order to predict the vulnerability and variation of the safety margins of a slope due to given rainfall, it is necessary to understand the mechanism of infiltration and resulting loss of matric suction, the possible developments of perched water table and the rise of the ground water table.

Analytical studies were done (Sujeevan and Kulathilaka, 2011) simulating the process of infiltration and illustrating the reduction of the safety factors with a prolonged rainfall (Kulathilaka and Sujeevan, 2011). Due to the absence of actual data on Sri Lankan residual soils basic characteristics such as SWCC and permeability functions available in literature were used in these studies. The findings of these studies highlighted the importance of establishing these basic characteristics for Sri Lankan residual soils.

The testing to determine these characteristics commenced after acquiring KU-tensimeters and other accessories such as data loggers. Tests are currently underway with undisturbed samples obtained from the site of the failed slope at Welipenna in the Southern expressway.

Once the basic characteristics are established it is planned to model the rainfall event to back analyze the failure. The case of failure at Welipenna would serve as a test case to calibrate the process of modeling and testing. With the establishment of the basic characteristics of the different soil layers in a given slope, the process of infiltration and resulting changes in the pore pressure regime can be modeled to a reasonable accuracy.

With the help of the KU-tensiometers it is possible to monitor the changes in the pore pressures in field from high matric suction values to positive pore water pressures during any given rainfall. The data acquired from the instrumented slope can be compared with the predicted changes from the modeling process. With such studies the process can be calibrated and it would be possible to establish threshold values of rainfall that could lead to failure in a given slopes of critical importance.

The process of monitoring will also be very helpful to assess the effectiveness of surface and subsurface drainage and surface protecting vegetation that would help to preserve the safety margins in given slope.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the research grant provided by NBRO for conducting the experiments. The KU-Tensiometers, data loggers and other accessories were provided by a Senate Research Grant obtained from the Department of Civil Engineering, University of Moratuwa. Pressure plate apparatus of the University of Moratuwa was used in this study. Permission granted to use these apparatus is gratefully acknowledged.

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