Properties of an Unsaturated Residual Soil behind a Failed Slope in Sri Lanka

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ABSTRACT: Rain-induced slope failures are common in Sri Lanka. With the infiltration of rainfall, the matric suction at upper levels of the slopes reduces, perched water table develops, ground water table rises and the shear strength diminishes making the slopes vulnerable. Basic characteristics such as; Soil Water Characteristic Curves (SWCC), permeability function and unsaturated shear strength parameters have not been established for typical residual soil slopes in Sri Lanka. Undisturbed samples of soil obtained behind the scar at the location of a failed slope at Welipenna in the Southern Expressway were used in this study. Direct shear tests and permeability tests were done and matric suctions were measured with a miniature tensiometer. Pressure plate apparatus was used to obtain the SWCC. The SWCC obtained by alternate techniques and empirical procedures were in reasonably good agreement. Contribution of matric suction to the shear strength found to be in agreement with finding of other researchers.

KEYWORDS: Soil water characteristic curve, Permeability function, Tensiometer, Unsaturated residual soil, Matric suction.

1. INTRODUCTON

Rain-induced failures in slopes made of residual soils are a major geotechnical hazard in Sri Lanka (Figure 1). Residual soils that 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. Ground water table is generally low in these conditions. The soils are therefore generally unsaturated and possess negative pore water pressures. Climatic changes greatly affect the soil properties, negative pore water pressure and shear strength of unsaturated soils.

Safety margins of these slopes are high during the periods of dry weather due to the prevailing matric suctions. Rainwater infiltration causes loss of matric suction. It may lead to development of perched water table conditions and also rise of ground water table.

Figure 1 Failed slope of Southern Transport Development Project (STDP) at Welipenna

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), University of Kasetsart in Thailand and by Standing (2012), Imperial College in London. Jotisankasa and Mairang (2010) conducted suction-monitored direct shear testing on some residual soils obtained from landslide-prone areas in Thailand to determine the relationship between apparent cohesion and suction. Estimation of soil suction from the soil-water characteristic curve was studied by Fredlund et al. (2011). Fredlund (2015) studied the relationship between the laboratory determined SWCC and the field stress state. Jotisankasa et al. (2015) studied the response of the pore water pressure regime and stability to rainfall in a granitic fill slope in Northern Thailand. The effect of hysteresis of soil-water characteristic curve on infiltration under different climatic conditions was studied by Bashir et al. (2016). The role of the Soil-Water Characteristic Curve in Unsaturated Soil Mechanics was highlighted by Fredlund (2017).

Numerical studies were done simulating the process of infiltration through a typical cut slope (of 1:1 gradient) in an unsaturated residual soil formation (Sujeevan and Kulathilaka, 2011) illustrated the loss of matric suction, development of perched water table and reduction of safety margin as the rainfall progresses. These studies on typical cut slopes in Southern Expressway have used the characteristics of unsaturated soils available in literature in the absence of actual local data. The need to conduct experiments to evaluate data for soils encountered in Sri Lankan slopes is the focus in the current research project.

This paper presents results of the study on unsaturated residual soil obtained from the site of a failed slope in Welipenna, Sri Lanka. Research studies were conducted to determine; Shear strength characteristics-the variation of total cohesion with matric suction, Soil water characteristic curve (SWCC) and Permeability function-the variation of permeability with matric suction of the soils obtained from the site.

2. BACKGROUND

2.1 Behaviour of unsaturated soils

Soil is a heterogeneous material consisting of pores of different geometries. Unsaturated soil is a four-phase system, namely solid, water, air and contractile skin (Fredlund and Morgenstern, 1977). The most distinctive property of the air-water interface (i.e., contractile skin) is its ability to exert a tensile pull such that contractile skin is always subjected to an air pressure of u_a, which is greater than the water pressure u_w. This pressure difference existing in soils due to the presence of liquid and gas phases is called matric suction.

Matric suction contributes additional strength to the soil structure. The compressive force exerted on the soil particles in the walls of interconnected pores (which behave as the capillary tube) produces this additional strength which is capable of enhancing the stability of the soil structure. This additional strength is quite significant especially in slopes as it provides that additional amount of resistance required to keep the slope stable.

Kulathilaka and Sujeevan (2011) illustrated that the loss of matric suction with infiltration has a direct impact on shallow seated slips which are encountered above the ground water table. This is due to the fact that infiltration of water into the slope once the rainy season starts saturates the soils above the groundwater table creating positive pore water pressures sometimes perched water table.

2.2 Shear strength of an unsaturated soil

As there are many constructions carried out on unsaturated soils, it is important to know the amount of shear strength contributed to the soil by suction. Also, the design engineers should have an idea about the process of infiltration. The shear strength of an unsaturated soil, τ can be expressed as Eq. (1) (Fredlund and Rahardjo, 1993). Ho and Fredlund (1982) proposed the concept of apparent cohesion and used it in the three-dimensional extended Mohr-Coulomb Failure Criterion. The matric suction term in the shear strength equation contributing to the cohesion for an unsaturated soil can be considered as Eq. (2)

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (1)$$

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

Where,
c' = Effective cohesion intercept,
σ = Normal total stress,
u_a = Pore air pressure (for atmospheric pressure, u_a equals zero),
u_w = Pore water pressure,
ϕ' = Effective angle of shearing resistance, and
ϕ^b = Angle of shearing resistance due to suction
c = Total or apparent cohesion of the soil

Gan and Fredlund (1988) and Escario and Juca (1989) showed that shear strength versus soil suction relationship over a selected range of soil suctions is non- linear and the concept has been strengthened further by other researchers, e.g., Vanapalli et al. (1996), Jotisankasa et al. (2010) and Jotisankasa et al. (2015).

2.3 Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve (SWCC) for a soil is defined as the relationship between water content (soil wetness) and suction of the soil. SWCC is also called the Soil Water Retention Curve. What is of great concern in an unsaturated soil is the transition zone, 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.

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 total suction of a soil is made up of two components, namely, the matric suction and the osmotic suction. For most geotechnical problems involving unsaturated soils, matric suction changes can be substituted for total suction changes (Fredlund and Rahardjo, 1993).

Degree of saturation, S_r, gravimetric water content, w, or volumetric water content, θ, are all related by Eq. (3),

$$\theta = V_w/V = wG_s/(1+e) = S_r e/(1+e) \quad (3)$$

As already outlined, SWCC is required as a key property for detailed analysis of slope behaviour including infiltration, and prediction of unsaturated shear strength. The shear strength of an unsaturated soil is related to the prevailing matric suction. Jotisankasa and Vathananukij (2008) made use of the SWCC to estimate the amount of rainfall required to reduce the suction to zero or saturate the slope.

2.4 Permeability function

There is no engineering soil property that can vary more widely than the coefficient of permeability. It differs by many orders of magnitude within different soil types and in a given unsaturated soil the variation with the saturation level is also over several orders of magnitude. The process of infiltration of water into an unsaturated soil is controlled by its permeability which will vary continuously as water gets stored in voids previously filled with air.

Therefore, the coefficient of permeability of unsaturated soils and its relationships to matric suction and volumetric water content are of major importance in the analyses of flow in saturated/ unsaturated soil media. A proper evaluation of the coefficient of permeability will make the saturated/ unsaturated flow analysis more accurate. In experimental determinations of coefficient of permeability, the soil under consideration is commonly assumed to be of constant volume. However, soil is known to behave as a deformable porous medium. In order to properly deal with soils as a deformable porous medium and to establish a better coefficient of permeability, the change in total volume of the soil specimen should be monitored. This was performed by Huang et al. (1995) using a specially designed triaxial permeameter.

This paper presents laboratory tests conducted similar to the approaches developed at Kasetsart University (KU), Thailand by Jotisankasa et al. (2010). The undisturbed sample instrumented with three KU tensiometers at different heights on different plan locations for the permeability cell is illustrated in Figure 2.

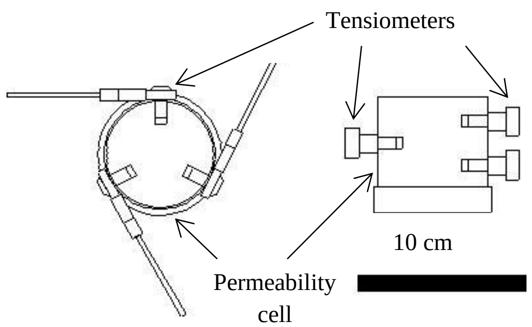


Figure 2 Arrangement of KU tensiometers in permeability cell

The values of suction at three locations can be used to calculate the hydraulic gradient, i, as in Eq. (4);

$$i = d\,(z - s/\gamma_w)/\,dz \quad (4)$$

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. 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 in Eq. (5);

$$v = dV_w/\,Adt \quad (5)$$

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. (6).

$$k = v/\,i \quad (6)$$

3. METHODOLOGY

This paper presents the results of studies conducted to determine the variation of unsaturated shear strength parameters of residual soil obtained from the site of a failed slope at Welipenna in Southern Expressway.

3.1 Rate of shearing for direct shear tests

It was necessary to use an appropriate shearing rate for testing of the samples in the direct shear box to ensure drained conditions. Coefficient of consolidation determined on saturated samples were of order of 3.8m^2/yr based on t_{90}. Based on that, it was decided to use a shearing rate of 0.125mm/min to ensure drained conditions during shearing.

3.2 Determination of shear strength parameters

Direct shear tests were conducted on undisturbed specimen of soil, varying the degree of saturation from natural to full saturation. This was achieved by systematic wetting of specimen. The weights and moisture contents were determined on each specimen to ascertain the degree of saturation. In all the unsaturated samples, direct shear tests were done while monitoring the matric suction. There are several methods for measurement of matric suction such as; axis-translation, tensiometer, filter paper etc. (Fredlund and Rahardjo, 1993). In this research a miniature tensiometer consisting of a Micro Electro Mechanical System (MEMs) pressure sensor with 1Bar High-Air-Entry porous ceramic tip developed at the University of Kasetsart, Thailand (Jotisankasa and Mairaing, 2010) is used.

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 detail by Jotisankasa (2010). The miniature tensiometer used in this study was capable of measuring suction from a value of zero to 100kPa. This smaller range of suction is however quite sufficient for slope stability studies. During testing, evaporation from the soil specimen was prevented by using plastic wrap and pieces of wet cloths to cover the whole shear box. This type of suction monitored shearing test thus offers alternative method for characterizing unsaturated shear strength in slope stability studies. The test setup is illustrated in Figure 3.

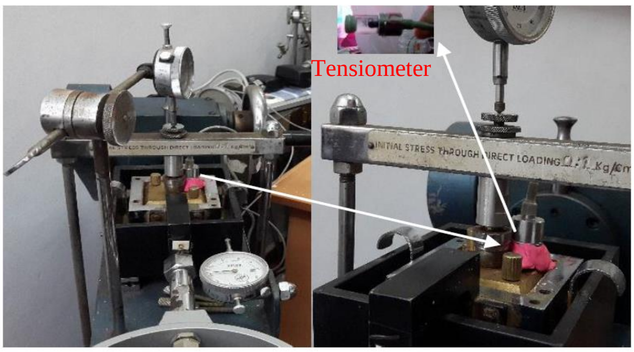


Figure 3 KU tensiometer and its incorporation in direct shear box (modified from Jotisankasa and Mairaing, 2010)

3.3 Determination of Soil Water Characteristic Curves (SWCCs)

Soil water characteristic curves (SWCCs) were determined using the methods described below.

3.3.1 Pressure plate apparatus

Samples were brought to equilibrium under different matric suctions by maintaining different values of matric suction equal to differences in air and water pressures (u_a - u_w) in the pressure plate apparatus for a sufficiently long period.

The time period was confirmed by observing no volume change through outflow tube.

3.3.2 Direct shear data with KU tensiometer

A number of samples of different levels of saturation achieved by adding a calculated amount of water were subjected to direct shear tests at four normal stresses which were confirmed by data. The matric suction and volumetric water content were measured in all these samples. Measurements were done both before and after the test.

3.3.3 Method of continuous measurement with KU tensiometer

A technique referred to as method of continuous measurement, which is also used to determine permeability function based on the simplified instantaneous profile principle (e.g. Hillel, 1998, Benson and Gribb, 1997) was also used to determine the SWCC. 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 100kPa to 0kPa).

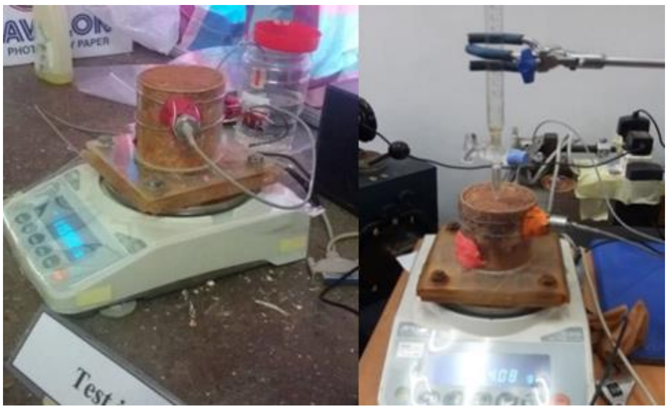
3.3.4 Gradation curve

A physico-empirical model proposed by Arya and Paris (1981) was used to predict the volumetric water content-suction relationship of a soil from its particle-size distribution, dry density and specific gravity. This approach is based on the transformation of a particle size distribution into a pore-size distribution. The cumulative pore volumes corresponding to progressively growing pore radii are divided by the sample dry density to give the volumetric water contents and the pore radii are converted to equivalent soil suctions using the equation of capillarity. The formulation is based on an empirical parameter, α, used to fit the experimental results to the model. The SWCC predicted by this method was compared with the experimental curves obtained to assess whether the technique can be used for local soils confidently when tests cannot be done.

3.4 Determination of permeability function

Permeability function is one of the most sophisticated parameters to measure of unsaturated soils. Usually, some kind of approximation based on the SWCC is carried out. Lu and Likos (2004) gives an overview of different techniques used to determine permeability function.

Based on the simplified instantaneous profile principle, continuous measurements of weight of the sample were taken with time while measuring matric suction for drying and wetting conditions as shown in Figure 4. The height and diameter of the sample are 8.2cm and 7.5cm respectively. The rate of movement of water is very small and determined through the weight loss/gain by an electronic balance which measures to an accuracy of second decimal of a gram at 1min interval. Linear regression over about 100 data points was used in calculating the values of flux, v.



Drying path Wetting path

Figure 4 Permeability function test for drying/wetting path test

Further, elevations from a reference level (base of the mould) of each tensiometer and other required parameters were measured for the purpose of the analysis. Previous research experience earned by Jotisankasa et al. (2010) and Mairaing et al. (2012) suggests that the value of hydraulic gradient, i, calculated over only the upper and middle pore pressure measurement gives better results of k-function than calculated over three measurements. This is perhaps due to non-uniformity of the pore water pressure distribution. Based on that experience, hydraulic gradient was calculated and plotted against matric suction of top and middle levels only. These data were used to obtain SWCC also.

4. RESULTS AND DISCUSSION

4.1 Basic characteristics of soil

Particle size distribution curve for the soil tested is presented in Figure 5. The soil was classified as MS according to the British Soil Classification System (BSCS) and as MH under Unified Soil Classification System (USCS). Index properties are summarized in Table 1. The specific gravity was 2.66. The permeability of the soil under saturated conditions was found to be 2.12x10^{-6}m/s.

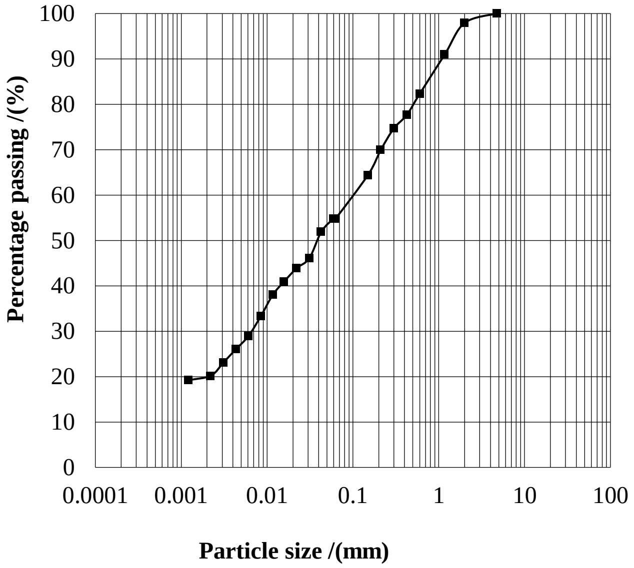


Figure 5 Particle size distribution

Table 1 Index properties of soil

Parameters	Value
Classification	MS/MH
Liquid limit/(%)	54
Plastic limit/(%)	43
Plasticity index/(%)	11
Gravel/(%)	2
Sand/(%)	43
Silt/(%)	35
Clay/(%)	20

4.2 Establishment of shear strength parameters

4.2.1 Fully saturated condition

Initially, the tests were performed after making the specimen fully saturated. The basic data are presented in Table 2.

All the direct shear tests were done ensuring drained condition. The loaded sample was allowed to consolidate for 24hours and was sheared at the rate of 0.125mm/min.

The stress – strain curves were obtained for normal stress of 50, 100, 150 and 200kPa as shown in Figure 6 and the shear strength envelope is presented in Figure 7. The saturated shear strength parameters are c′=18kPa and ϕ′=33º.

Table 2 Basic characteristics of tested specimen for fully saturated condition

Parameters	Value			
Specimen No.	1	2	3	4
Moisture content/ (%)	49.08	43.77	44.81	42.11
Degree of saturation (%)	100	100	100	100
Volumetric water content/ (%)	56.26	52.73	53.92	52.14
Dry density /(kg/m^3)	1146	1205	1203	1238
Void ratio	1.27	1.16	1.16	1.10

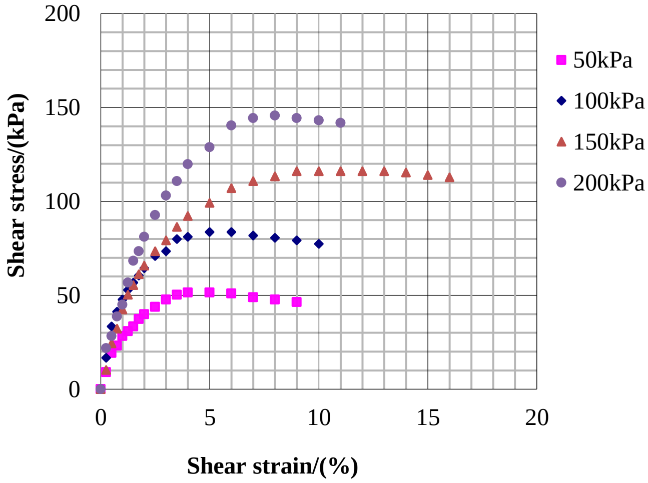


Figure 6 Variation of shear stress with shear strain for fully saturated condition

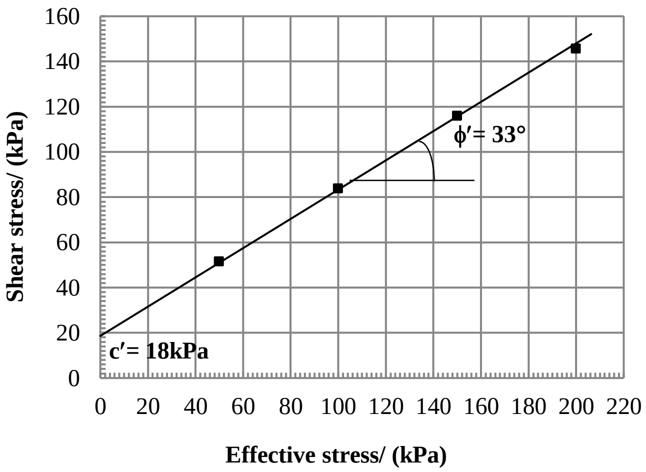


Figure 7 Variation of shear stress with normal stress for fully saturated condition

In the subsequent tests, the degree of saturation of the undisturbed sample was changed by controlled wetting. A calculated amount of water was added to the tested soil specimen to achieve target degrees of saturation of 65%, 72%, 81% and 92%. The details for approximately 81% saturated condition are given in Section 4.2.2. After the tensiometer was attached to the sample it was kept until the readings reached equilibrium (minimum 24hours).

Thereafter, the normal stress was applied and sample was consolidated for 24hours. This was followed by shearing under drained conditions at the rate of 0.125mm/min. Matric suction was monitored throughout the test.

Based on Fredlund and Rahardjo (1993), ϕ′ value of 33º obtained from fully saturated direct shear test was used to determine the cohesion intercepts for all unsaturated samples.

4.2.2 Tests at saturation level of 81%

The basic characteristics of the samples with the target of 81% saturation are presented in Table 3. The stress-strain curves and shear strength envelope are presented in Figure 8 and Figure 9 respectively. Equilibrium, consolidation and shearing stages were conducted while monitoring the matric suction as presented in Figure 10, Figure 11 and Figure 12 respectively.

Table 3 Condition of tested specimen for approximately 81% saturated condition

Parameter		Value			
Specimen No.		1	2	3	4
Moisture content/ (%)	Before	34.42	30.66	34.14	32.35
	After	34.78	30.96	34.99	31.31
Degree of saturation/ (%)	Before	77.08	76.61	76.96	77.40
	After	80.16	83.74	84.58	87.71
Volumetric water content/ (%)	Before	41.41	39.06	41.22	40.31
	After	42.49	41.04	43.83	42.22
Dry density /(kg/m^3)	Before	1203	1274	1207	1246
	After	1222	1326	1252	1348
Void ratio	Before	1.16	1.04	1.15	1.09
	After	1.13	0.96	1.08	0.93

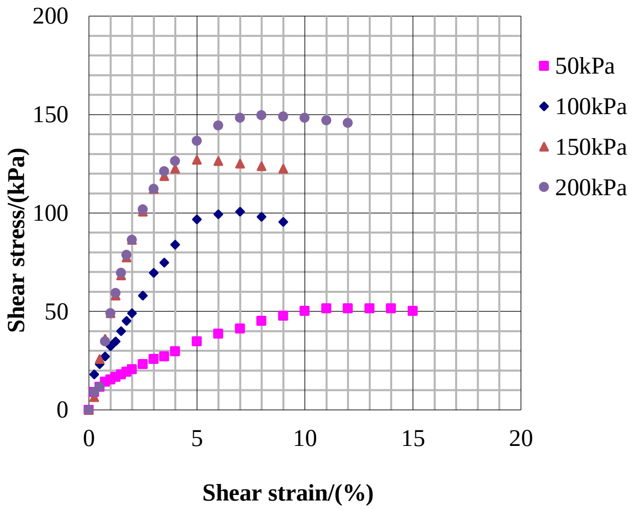


Figure 8 Variation of shear stress with shear strain for approximately 81% saturated condition

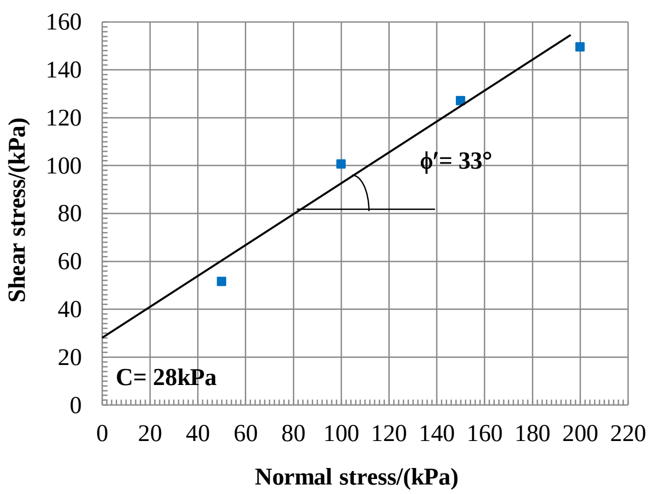


Figure 9 Variation of shear stress with normal stress for approximately 81% saturated condition

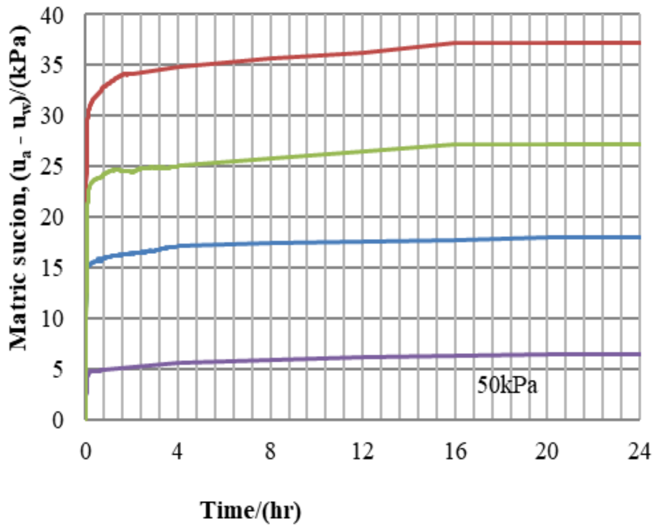


Figure 10 Variation of matric suction with time at equilibrium stage for approximately 81% saturated condition

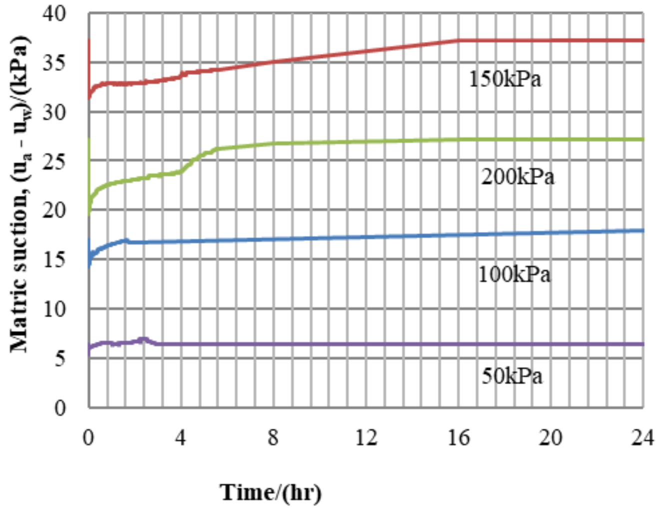


Figure 11 Variation of matric suction with time at consolidation stage for approximately 81% saturated condition

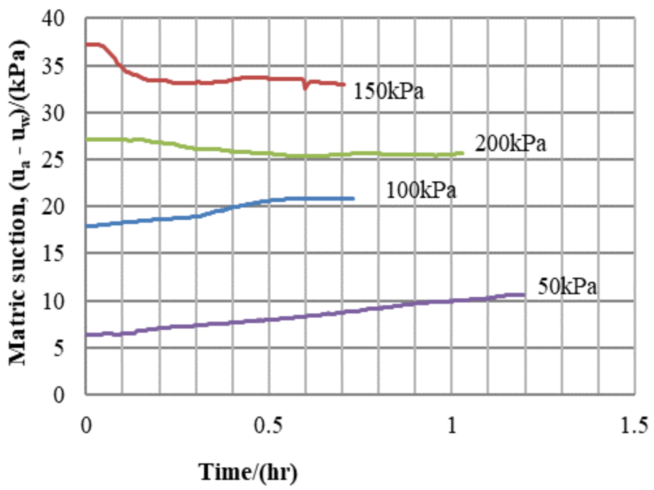


Figure 12 Variation of matric suction with time at shearing stage for approximately 81% saturated condition

The apparent cohesion intercepts obtained from the direct shear tests on samples of different levels of saturation are presented along with measured average matric suction in Table 4. The variation of average matric suction with the average degree of saturation is graphically presented in Figure 13.

Table 4 Unsaturated parameters obtained from the direct shear tests for sandy silt of $\phi' = 33°$

Test No.	Degree of saturation/ (%)	Measured apparent cohesion, C/ (kPa)	Measured average matric suction, $(u_a - u_w)$/ (kPa)
1	50	-	≥ 100
2	65	38	65
3	72	32	56
4	81	28	22
5	92	24	3
6	100	18	0

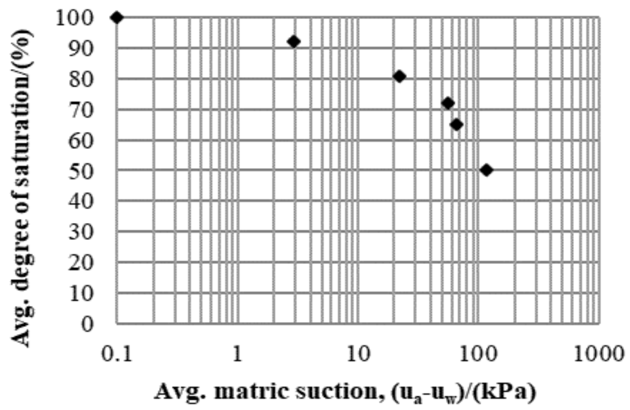


Figure 13 Variation of average degree of saturation with average matric suction- (based on Direct Shear test data)

4.2.3 Development of angle of shearing resistance due to suction, ϕ^b, using tensiometer apparatus

Peak shear strength (obtained from stress-strain curve) and relevant matric suction values for all the specimens used for the direct shear test with different levels of saturation are summarized in Table 5 for each normal loading category. The variation is graphically presented for the normal stress range of 50kPa – 200kPa in Figure 14.

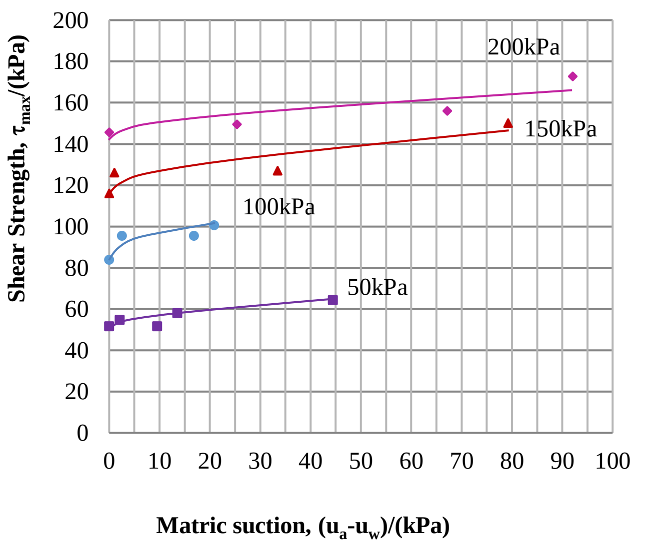


Figure 14 Variation of maximum shear strength (at failure) with matric suction for 50kPa – 200kPa of net normal stress

Table 5 Variation of shear strength with matric suction for different degree of saturation levels

Normal stress/ (kPa)	Degree of saturation/ (%)	Shear strength/ (kPa)	Measured matric suction at failure, (u_a-u_w)/ (kPa)
50	65	64.26	44.48
	72	58.03	13.58
	81	51.58	9.55
	92	54.80	2.09
	100	51.60	0.00
100	65	131.14	58.06
	72	95.42	16.87
	81	100.58	20.90
	92	95.42	2.54
	100	83.80	0.00
150	65	200.00	87.01
	72	150.22	79.25
	81	127.01	33.43
	92	126.07	1.04
	100	116.10	0.00
200	65	156.06	67.16
	72	172.79	92.09
	81	149.58	25.37
	92	169.72	0.45
	100	145.70	0.00

The variation of apparent cohesion with average matric suction derived from these tests is presented in Figure 15. The five points in the plot represent the four levels of suction used and the saturated state. It could be seen that ϕ^b value is not a constant. This is in agreement with the findings of Gan and Fredlund (1988), Escario and Juca (1989), Vanapalli et al. (1996) and Jotisankasa et al. (2010) as discussed in Section 2.2.

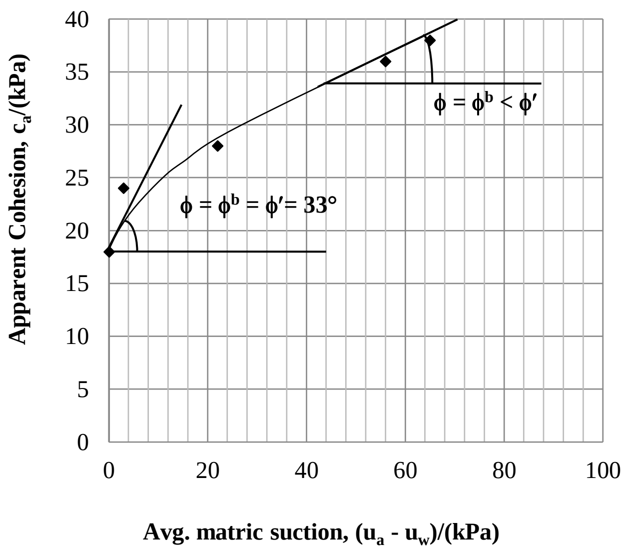


Figure 15 Variation of apparent cohesion with average matric suction

Residual soils, especially those formed by weathering of metamorphic parent rock, are highly heterogeneous. The composition of the weathered product can change abruptly. Whitish clay formed by weathering of rocks with high feldspar content was seen at the shear surface as depicted in Figure 16.

Figure 16 Direct shear specimens after the testing

4.3 Establishment of soil water characteristic curve

Various methods could be used to determine the SWCC as mentioned in previous sections. SWCCs of intact undisturbed samples determined using pressure plate apparatus, direct shear data with KU tensiometer, method of continuous measurement with KU tensiometer and grading curves are presented proceeding sections.

4.3.1 SWCC using pressure plate apparatus

Average volumetric water content was determined by obtaining the weights of all four samples under equilibrium conditions for each level of matric suction (u_a - u_w) as shown in Figure 17. As the air entry value of the porous disc was 500kN/m^2 the curve could be extended to 400kN/m^2 beyond the result achieved with the tensiometer.

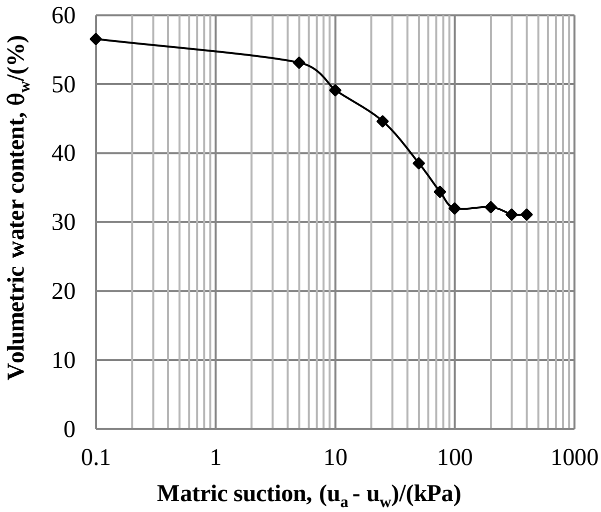


Figure 17 Variation of volumetric water content with matric suction (SWCC) derived using pressure plate apparatus

4.3.2 SWCC using direct shear data with KU tensiometer

Soil Water Characteristic Curve (SWCC) for the tested soil obtained by assembling all the data from the direct shear test are presented in Figure 18.

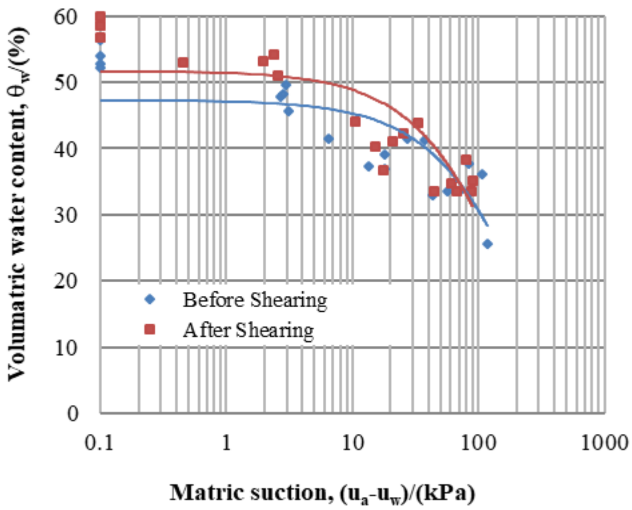


Figure 18 Variation of volumetric water content with matric suction (SWCC) using direct shear data with KU tensiometer

4.3.3 SWCC using method of continuous measurement with KU tensiometer

Besides the function of permeability at different suctions, volumetric water contents can also be determined from this test and some of the outputs during drying and wetting paths are given in Figure 19. Then drying curve is more reliable but wetting curve can be subjected to experimental errors as discussed in the summary.

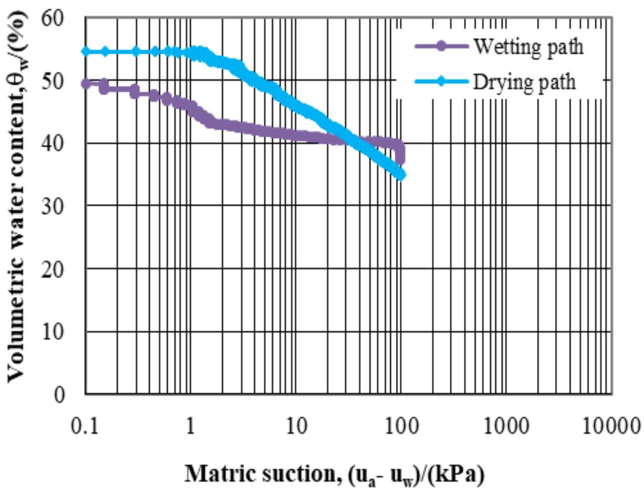


Figure 19 Variation of volumetric water content with matric suction (SWCC) using method of continuous measurement with KU tensiometer

4.3.4 SWCC using grading curve

The relationship between volumetric water content and matric suction from drying method have been used to calculate the empirical model parameter, α, for each soil type as displayed in Figure 20.

The reasonable best fit of volumetric water content vs. matric suction plotted from gradation curve is shown in Figure 21 and the comparison of SWCCs from various methods discussed is presented in Figure 22. Detail derivations of this method are given in Vasanthan (2016).

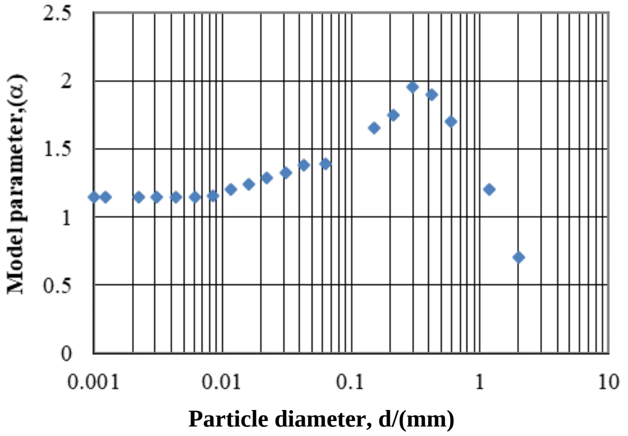


Figure 20 Variation of model parameter with particle diameter

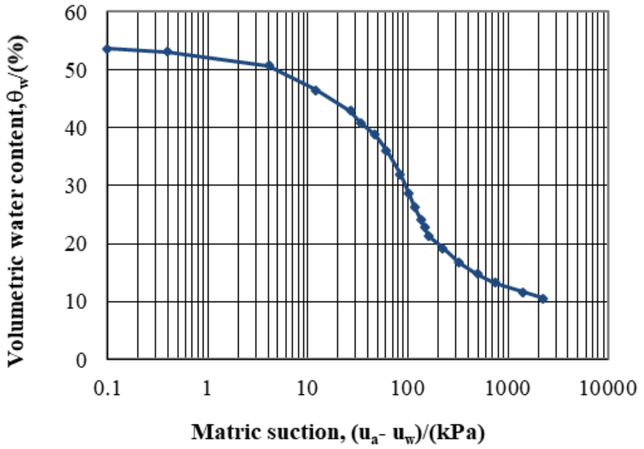


Figure 21 Variation of volumetric water content with matric suction (SWCC) derived using grading curve

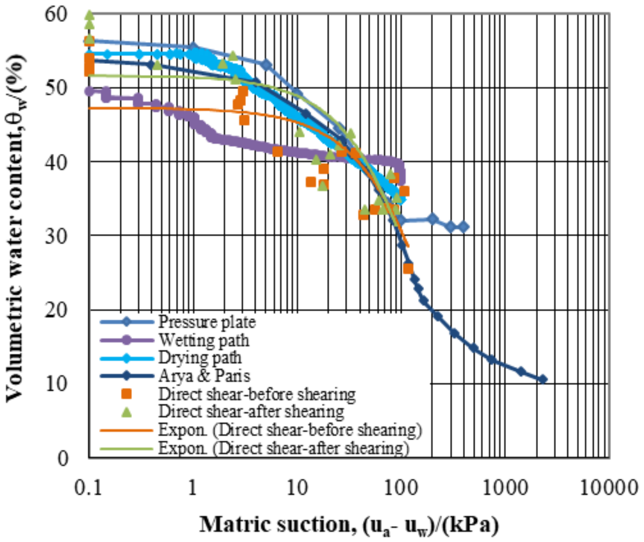


Figure 22 Comparison of SWCCs from various methods

4.4 Establishment of permeability function

Permeability functions were developed using drying and wetting methods.

4.4.1 Drying method

For the determination of permeability by drying method, the top surface of soil sample was left exposed to ambient air, and the soil suction was monitored continuously at two locations as shown in Figure 4.

Matric suction was measured continuously and graphically presented in Figure 23. There is not much deviation observed in matric suction values for top and middle positions of the tensiometers.

Hydraulic conductivity was calculated using the procedure described in Section 2.4 and the variation of hydraulic conductivity with matric suction is graphically presented in Figure 24.

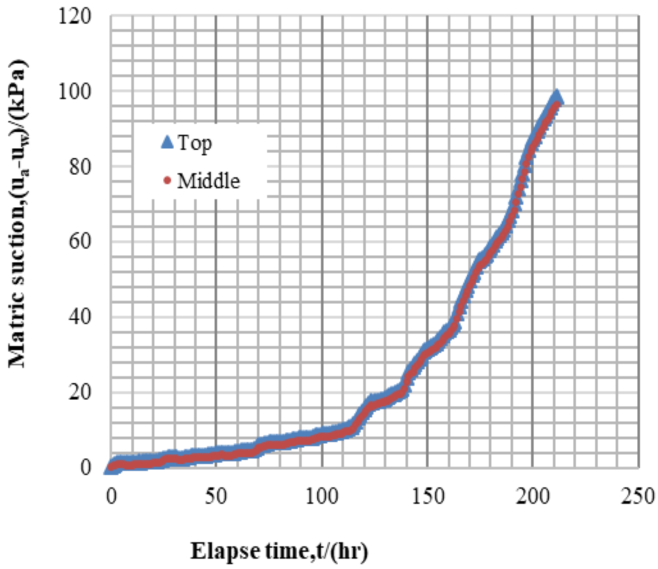


Figure 23 Variation of matric suction with time

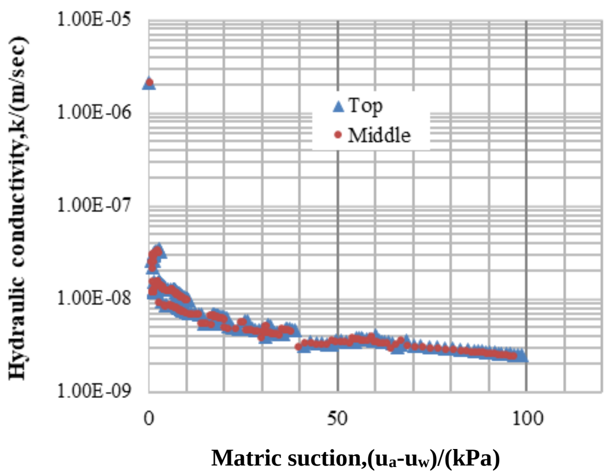


Figure 24 Variation of hydraulic conductivity with matric suction

4.4.2 Wetting method

For the determination of permeability by wetting method, the top surface of sample is continuously wetted by way of water dripping at a constant rate from burette as shown in Figure 4.

Other procedures followed were same as in drying method and matric suction was measured continuously and graphically presented in Figure 25. Hydraulic conductivity was calculated using the procedure described in Section 2.4 and the variation with matric suction is graphically presented in Figure 26.

There are little deviations observed in matric suction values for top and middle positions of the tensiometers.

There were some small peaks at initial stage of wetting path (dry condition, hence high matric suction). This was due to the non-homogeneous infiltration process which depends on crack pattern developed on the top surface of the soil specimen due to very dry condition at the top surface. The water diminished through surface cracks encountered due to shrinkage during the drying process. This water filled the pores up to a certain depth of the soil specimen from the top and that areas appear to be of slightly higher permeability as it has a high level of saturation than other areas temporarily until the uniform infiltration is created throughout the whole depth of the soil specimen. This results in some temporary peaks in permeability.

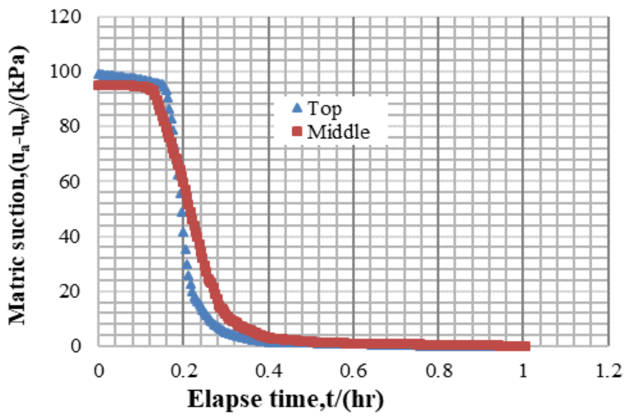


Figure 25 Variation of matric suction with time

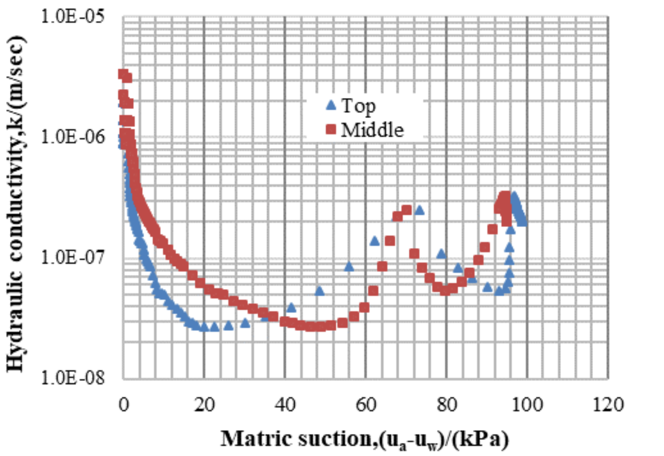


Figure 26 Variation of hydraulic conductivity with matric suction

5. SUMMARY AND CONCLUSIONS

Soil characteristics necessary for modelling the infiltration process were determined in this research. Tests on pressure plate apparatus, suction monitored permeability tests and suction monitored direct shear tests were conducted to determine these characteristics.

Four different levels of degree of saturation were obtained by controlled wetting of the samples. Four stress levels were used for each degree of saturation. Matric suction for a particular degree of saturation level should be within the similar range at the equilibrium stages. However, in this study, there were some variations which could be attributed to the non-homogeneity of the soil. The plots, variation of shear strength with the average matric suction and the variation of the apparent cohesion with the matric suction, demonstrated similar trends observed by other researchers.

The soil-water characteristic curves as well as the permeability-suction function were determined on residual soil for both wetting and drying paths. A method based on continuous drying and wetting the soil sample while continuously monitoring the suction gradient and the change in soil mass was used. The advantage of this method is that the SWCC and k-function of an undisturbed sample can be determined in the suction range of 0 to 100kPa within a week.

The difference in the wetting SWCCs obtained from various test methods appear to be greater than that of drying SWCCs. This is believed to be due to the greater non-linearity of the suction distribution in the wetting tests. There is nevertheless difficulty in using this technique for wetting tests due to non-linearity of the matric suction under non-uniform or variable infiltration which depends on dry density, structural arrangement of soil particles, mineral composition, crack pattern developed on the top surface of the soil specimen and soil type. This method is still not very accurate for wetting path.

The hydraulic gradient "i" appears to vary nonlinearly with time. The negative value of "i" suggests upward movement of water or net evaporation. The drying k-function however appears to be of less scatter than the wetting, possibly due to the less non-linearity of the suction distribution during drying test as described previously. The drying path with continuous technique thus offers a very quick and simple way for k-function determination of unsaturated soils.

6. FUTURE OUTLOOK

This technique can be now extended to many other important slopes to obtain a set of curves and parameters corresponding to typical soil types encountered. Once these characteristics are well established it would be possible to model the infiltration process and changes in the pore pressure regime for a given rainfall pattern. Thereafter, stability analyses could be conducted to establish the variation of the safety margin during a prolonged rainfall event. With the help of the KU-tensiometers it is possible to monitor the changes in the pore pressures in the field from high matric suction values to positive pore water pressures during any given rainfall event. 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 refined. Such a series of studies would help to establish threshold rainfall intensities for critical slopes.

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8. REFERENCES

Arya, L.M., and Paris, J.F. (1981) "A physic-empirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data", Soil Sci. Soc. Am. J. 45, pp1023–1030.

Bashir, R., Sharma, J., and Stefaniuk, H. (2016) "Effect of hysteresis of soil-water characteristic curve on infiltration under different climatic conditions", Canadian Geotechnical Journal, Vol. 53, pp273-284, dx.doi.org/10.1139/cgj-2015-0004.

Benson, C. and Gribb, M.M. (1997) "Measuring unsaturated hy-draulic conductivity in the laboratory and field", Unsaturated Soil Engineering Practice. Proceedings of sessions on unsaturated soils at Geo -Logan '97. The Geo-Institute/ASCE. Logan, Utah.

Escario, V., and Juca. J. (1989) "Shear strength and deformation of partly saturated soils", Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janerio, 2, pp43-46.

Fredlund, D. G. (2017) "Role of the Soil-Water Characteristic Curve in Unsaturated Soil Mechanics", Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea, Sept 17-22.

Fredlund, D.G. (2015) "Relationship between the laboratory SWCC and the field stress state", Proceedings of the Sixth Asia-Pacific Conference on Unsaturated Soils, Quilin, China, October, pp23-26.

Fredlund, D.G., and Morgenstern, N.R. (1977) "Stress state variables for unsaturated soils". Journal of the Geotechnical Engineering Division., ASCE, Vol. 103, No. GT5, proc. Paper 12919, May, 1977, pp447-466.

Fredlund, D. G., and Rahardjo, H. (1993) "Soil mechanics for unsaturated soils", New York: Wiley.

Fredlund, D.G., Sheng, D., and Zhao, J. (2011) "Estimation of soil suction from the soil-water characteristic curve", Canadian Geotechnical Journal, Vol. 48, No. 2, pp186-198.

Gan, J.K.M., and Fredlund, D.G. (1988) "Multistage direct shear testing of unsaturated soils", American Society for Testing Materials, Geotechnical Testing Journal, 11(2), pp132-138.

Hillel, D. (1998) "Environmental soil physics", Academic Press.

Ho, D.G., and Fredlund, D.G. (1982) "A multistage triaxial test for unsaturated soils", Geotechnical Testing Journal, 5(1), pp18-28.

Huang, S.Y., Fredlund, D.G., and Barbour, S.L. (1995) "Measurement for the coefficient of the permeability of an unsaturated soil", 1st int. conf. on Unsaturated Soils, Paris, Paper No. 99.

Jotisankasa, A. (2010) "Manual for user of KU Tensiometer", 2nd edition, Geotechnical Innovation Laboratory, Geotechnical Engineering Research and Development Center, GERD, Kasetsart University, Thailand.

Jotisankasa, A., and Mairaing, W. (2010) "Suction-monitored direct shear testing of residual soils from landslide-prone areas", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 136, No. 3, March 1, 2010.

Jotisankasa, A., and Vathananukij, H. (2008) "Investigation of soil moisture characteristics of landslide-prone slopes in Thailand". Proc. of the International Conference on Management of Landslide Hazard in the Asia-Pacific Region, Sendai, Japan, November 11-15.

Jotisankasa, A., Kulsuwan, B., Toll, D., and Rahardjo, H. (2008) "Studies of rainfall-induced landslide in Thailand and Singapore", The First European Conference on Unsaturated Soils (E-UNSAT), 2-4 July, 2008, Durham, UK, pp901-907.

Jotisankasa, A., Mahannopkul, K., and Sawangsuriya, A. (2015) "Slope Stability and Pore-Water Pressure Regime in Response to Rainfall: a Case Study of Granitic Fill Slope in Northern Thailand", Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 46 No.1 March 2015 ISSN 0046-5828.

Jotisankasa, A., Tapparnich, J., Booncharoenpanich, P., Hunsachainan, N., and Soralump, S. (2010) "Unsaturated soil testing for slope studies", Proc. International conference on Slope, Thailand, Geotechnique and Geosynthetics for Slope, Chiangmai, Thailand.

Kulathilaka, S.A.S., and Sujeevan, V. (2011) "Rain Triggered Slope Failures in Unsaturated Residual Soils", Published in the Journal of the Sri Lankan Geotechnical Society, Sri Lanka.

Lu, N. and Likos, W.J. (2004) "Unsaturated soil mechanics", Wiley.

Mairaing, W., Jotisankasa, A., and Soralump, S. (2012) "Some Applications of Unsaturated Soil Mechanics in Thailand: an Appropriate Technology Approach", Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 43 No.1 March 2012 ISSN 0046-5828.

Rahardjo, H., Leong, E. C., Deutscher, M. S., Gasmo, J. M., and Tang, S.K. (2000) "Rain Induced slope failures", Geotechnical Engineering Monograph 3 - Published by the Nanyang Technological University, Singapore.

Standing, J.R. (2012) "The Development of Unsaturated Soil Mechanics at Imperial College, London", Geotechnical Engineering Journal of the SEAGS &AGSSEA Vol. 43 No.1 March 2012 ISSN 0046-5828.

Sujeevan, V., and Kulathilaka, S.A.S., (2011) "Rainfall Infiltration Analysis in Unsaturated Residual Soil slopes", Published in the Journal of the Sri Lankan Geotechnical Society, Sri Lanka.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., and Clifton, A.W. (1996) "Model for the prediction of shear strength with respect to soil suction", Canadian Geotechnical Journal, Vol. 33, pp 379-392.

Vasanthan, N. (2016) "Establishment of Fundamental Characteristics of Unsaturated Sri Lankan Residual Soils", M.Eng thesis submitted to the University of Moratuwa, Sri Lanka.