Shear strength and permeability characteristics of some Sri Lankan residual soils

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ABSTRACT: Sloping grounds in Sri Lanka are formed of residual soils with low ground water table and high matric suction during dry weather. Infiltration during prolonged rainfalls causes reduction in matric suction and perhaps development of perched water table, eventually leading to instability. Threshold values of triggering rainfalls are traditionally decided based on experience. Now, attempts are made to adopt an analytical approach after obtaining relevant engineering characteristics in the laboratory. This research was directed on compacted residual soils that form many road embankments and earth dams. Soil water characteristic curves (SWCC) were evaluated by different techniques and compared with that predicted by particle size distribution. Permeability function for both wetting and drying phases were investigated. Direct shear tests were done by modifying the conventional apparatus by incorporating KU tensiometer to measure matric suction.

1 INTRODUCTION

Residual soil formations encountered in Sri Lanka are derived from the weathering of metamorphic parent rock. During the periods of dry weather, ground water table is deep and near surface soil is in unsaturated state and pore water pressure (PWP) is negative. This negative PWP contributes to additional shear strength of soil and stability of the slopes. Infiltration during prolonged rainfalls can diminish this negative PWP to nearly zero. Perched water table can also be induced during heavy rainfall. This series of events can also take place in embankments made by compacted residual soil. Changes in the pore pressure regime will be the triggering factor for slope failures.

Threshold values of triggering rainfalls are traditionally decided based on experience and attempts are now made to enhance these predictions with instrumentation of slopes and analytical studies. Although some analytical studies were done simulating the process of infiltration and changes taking place in the pore pressure regime, unavailability of actual parameters for the modelling was a major drawback.

Vasanthan (2016) did a study for the first time in Sri Lanka to establish characteristics of an unsaturated soil (in an undisturbed state) obtained from a site of failed slope in Southern expressway. The soil within the block sample of 0.3 m x 0.3 m x 0.3 m was also found to be quite variable.

Hence, this study was done with a uniform soil typically used for construction of embankments. An embankment constructed with such material compacted with a water content near the optimum, will be in an unsaturated state. Basic characteristics such as; SWCC, permeability function and unsaturated shear strength parameters were determined in this study. SWCCs obtained by different techniques were compared with that derived from the particle size distribution.

2 PRELIMINARY EXPERIMENTAL STUDIES

Initially, the basic index properties of the soil were determined. Thereafter Standard Proctor compaction test was done to determine Optimum moisture content and maximum dry density. Consolidation tests and permeability tests were conducted after saturation of the samples compacted at optimum moisture content. 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 to ensure that testing is done under drained conditions.

2.1 *Soil type and index properties*

The soil for the study was obtained by excavation of a natural residual soil formation at the premises of University of Moratuwa. After excavation of the soil, particles greater than 5 mm in size were removed by sieving. The removal of larger size particles was done in view of the small sample thickness (order of 20 mm) in direct shear test and consolidation test to be conducted. Results from the wet sieve and hydrometer analysis reveal that the sand content is 44.13% and fines content is 55.50%. The basic characteristics of the soil are summarized in Table 1. It is classified as a high plastic silt (MH) according to the Unified Soil Classification System. The permeability determined by the falling head method, after saturation of the sample compacted at optimum water content is $2.74X10^{-9}$ m/s. This value was confirmed by repeated testing.

Table 1. Summary of measured index properties of the soil.

Index property	
Standard compaction tests	
Maximum dry density (kg/m^3)	1554
Optimum moisture content (%)	23.10
Particle size distribution	
Gravel content (> 4.75 mm, %)	0
Sand content (≤ 4.75 mm, %)	44.13
fines content (≤ 75 µm, %)	55.50
Specific gravity	2.61
Atterberg limits	
Plastic limit (%)	36.35
Liquid limit (%)	55.80
Plasticity index (%)	19.45
Unified soil classification system (USCS)	MH

2.2 *Consolidation test*

A set of consolidation tests were performed under saturated condition and values of coefficient of consolidation were in the range of 9-18 mm^2/min. Direct shear tests are to be conducted under drained conditions and the rate of shearing must be decided to ensure that 90% consolidation achieves much earlier than the failure. Accordingly, a rate of shearing of 0.125 mm/min was used.

3 SUCTION MEASUREMENT

The matric suction in a soil is defined as:

$$s = u_a - u_w \tag{1}$$

where, u_a is the pore air pressure (equal to zero atmospheric condition) and u_w is the pore water pressure. A miniature tensiometer developed at Department of Civil Engineering, Kasetsart University, Thailand was used to measure matric suction in this research. It consists of micro electro mechanical system (MEMs) pressure sensor, 1BAR High-Air-Entry porous ceramic and transparent acrylic tube as shown in Figure 1.

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

Figure 1. Miniature KU tensiometer sensor.

4 DETERMINATION OF UNSATURATED SHEAR STRENGTH PARAMETERS

Shear strength of an unsaturated soil can be expressed as:

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{2}$$

where, c' = effective cohesion; ϕ' = effective friction angle associated with net stress ($\sigma - u_a$); ϕ^b = friction angle associated with a change in suction ($u_a - u_w$).

Direct shear tests were conducted on; soil samples compacted at optimum moisture content, samples saturated after compaction and samples brought to a predetermined matric suction in the pressure plate apparatus. The specimen to be used in direct shear tests were placed in the pressure plate apparatus under a predefined matric suction until the equilibrium conditions are achieved. The weights and moisture contents were determined on each specimen to ascertain the degree of saturation. The tests were done under consolidated drained conditions and matric suction measurements were done throughout the testing. Figure 2 illustrates how the tensiometer is incorporated in the direct shear apparatus.

Figure 2. Direct Shear Apparatus incorporated with a tenisometer.

4.1 *Fully saturated condition*

Direct shear tests were conducted under the normal stresses of 50, 100, 150 and 200 KN/m^2. Initially, the tests were performed on fully saturated specimen. The saturated shear strength parameters are c′=23.9 KN/m^2 and ϕ′=32.6^o and these values were confirmed by repeated testing. The other samples were tested at different levels of saturation.

4.2 *Shear strength of samples at different degrees of saturation*

Samples compacted at optimum moisture content had a degree of saturation of 92%. The measured matric suction of this specimen was around 30 KN/m^2.

In order to obtain samples of different degrees of saturation, the specimen of compacted samples was placed in the pressure plate apparatus and brought to equilibrium under a predetermined matric suction. Matric suctions of 40 KN/m^2 and 60 KN/m^2 were used in this context. The tensiometer was placed on the sample and was allowed to reach equilibrium to measure and reconfirm the matric suction values. Thereafter, normal load was applied, and sample was allowed to consolidate and finally shearing was done while measuring the matric suction. The tensiometer achieving the equilibrium state and measuring the matric suction is illustrated in Figure 3. Variation of matric suction during consolidation state is presented in Figure 4 and Variation of matric suction with time during shearing stage is presented in Figure 5.

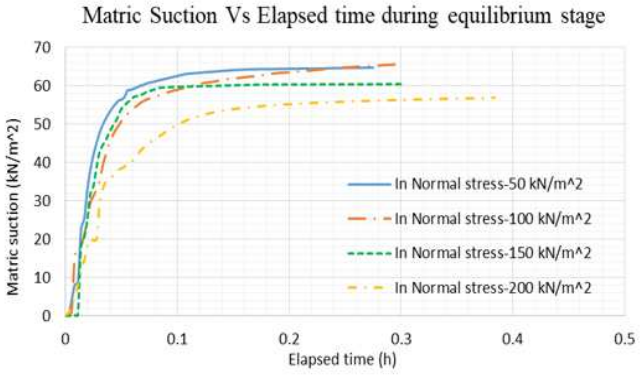

Figure 3. The variation of matric suction with time during equilibrium stage at 60 KN/m^2 matric suction.

It can be seen that, although the specimen were initially in equilibrium under a matric suction of 60 KN/m^2 at the preparatory stage (equilibrium state) some changes of matric suction have taken place during the consolidation. Matric suction has reduced at higher consolidation stresses and this change happens immediately after application of loads.

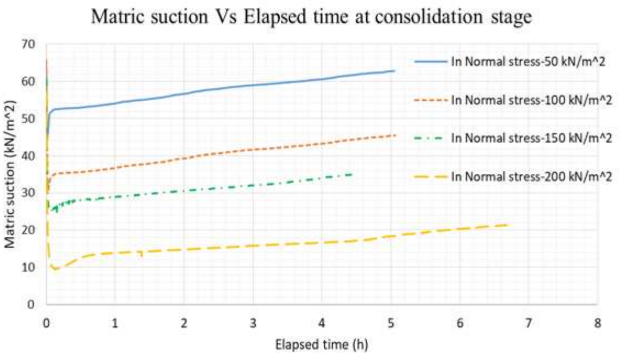

Figure 4. The variation of matric suction with time during consolidation stage at 60 KN/m^2 matric suction.

At shearing stage of each test, some compression was observed which was accompanied by a slight decrease in matric suction at the middle range as illustrated in Figure 4. Upon reaching the peak and ultimate state, matric suction increased gradually and then appeared to level off.

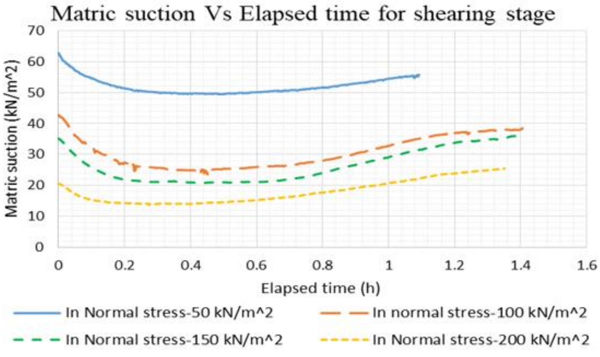

Figure 5. The variation of matric suction with time during shearing stage at 60 KN/m^2 matric suction.

A similar series of direct shear tests were done on specimen brought to equilibrium under a matric suction of 40 KN/m^2 and specimen in as compacted state (30 KN/m^2 matric suction).

Based on Fredlund and Rahardjo (1993), the same ϕ′ obtained from fully saturated direct shear test (32.6^o) was used for all unsaturated samples and the cohesion intercepts were determined accordingly. The data obtained are summarized in Table 2.

Table 2. Unsaturated parameters obtained from the direct shear tests for high plastic silt of ϕ′ =32.62°.

Test No.	Saturation/ (%)	Measured apparent cohesion, c_a/(kN/m^2)	Measured matric suction, u_a - u_w/ (kN/m^2)
1	81	58.6	60
2	85	50.9	40
3	92	42.1	30
4	100	23.9	0

4.3 *Development of angle of shearing resistance due to suction,* ϕ^b *using tensiometer*

The plot of apparent cohesion versus matric suction was done using the values obtained from the Table 2 and is presented in Figure 6. It can be seen that, the ϕ^b value is not a constant. Similar results were obtained by Vanapalli et al. (1996), Jotisankasa and Mairaing (2010) and Vasanthan (2016).

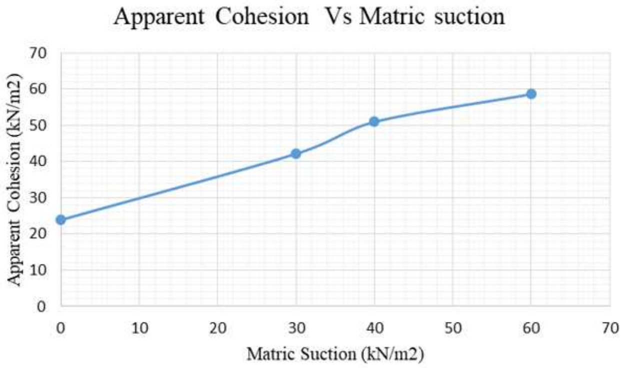

Figure 6. The variation of maximum shear strength (at failure) with matric suction for 50 KN/m^2 of normal load.

5 DETERMINATION OF PERMEABILITY FUNCTION

The compacted sample is instrumented with three KU-tensiometers at different heights on different plan locations. The values of suction at 3 locations can be used to compute the hydraulic gradient, *i*, is given by:

$$i = \frac{d(z - s/\gamma_w)}{dz} \quad (3)$$

where, z is the elevation head of each tensiometer relative to the base of sample; s is matric suction and γ_w is the unit weight of water.

As the quantity of flow is very small, the plot of change in soil mass was used to calculate the discharge velocity, *v*, at any particular time is given by:

$$v = \frac{dv_w}{dtA} \quad (4)$$

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.

The value of permeability at any suction and volumetric water content can then be calculated by Equation 5. (Jotisankasa et al. 2010):

$$k = \frac{v}{i} \quad (5)$$

5.1 *Shear strength of samples at different degrees of saturation*

For the drying and wetting tests, Jotisankasa et al. (2010) 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. Hence, this concept was used in this research for both drying and wetting paths.

Figure 7 presents the apparatus used and arrangement of tensiometers.

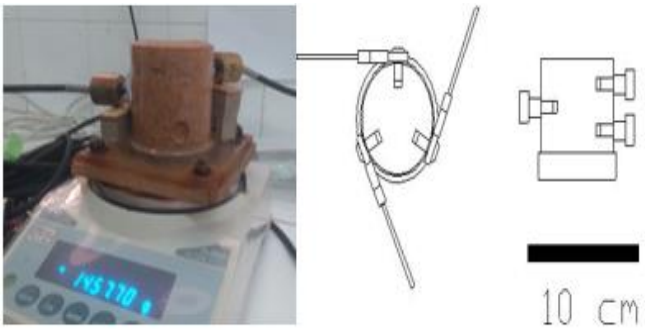

Figure 7. Arrangement of tensiometers for continuous measurement.

5.2 *Drying path*

For the drying method, the top surface of soil sample was left exposed to ambient air, and the soil suction was monitored continuously at two locations (upper and middle levels). Soil mass was also measured continuously using an electric balance connected to a data logger and hydraulic conductivity was calculated as mentioned in the Section 5.

5.3 *Wetting path*

For the determination of wetting method, the top surface of sample was continuously wetted by way of water dripping at a constant rate from burette. Evaporation during the test was negligible since the testing time was very short compared to drying path as shown in Figure 8.

Other procedures were followed same as drying method and matric suction and soil mass was measured continuously. Hydraulic conductivity was calculated as mentioned in the section 5.

The variation of matric suction with time during both drying and wetting paths are presented in Figure 8. It can be seen that, the suction loss was quite sudden in wetting path. The variation of hydraulic conductivity with matric suction during drying and wetting paths are presented in Figure 9 and Figure 10, respectively.

The main advantage of continuous measurement is the shortest test duration which is only a few days per one path. (From suction about 85 KN/m^2 to 0 KN/m^2.

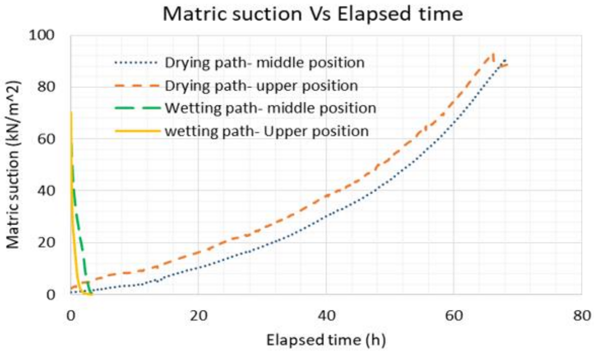

Figure 8. Variation of matric suction with elapsed time during drying and wetting paths.

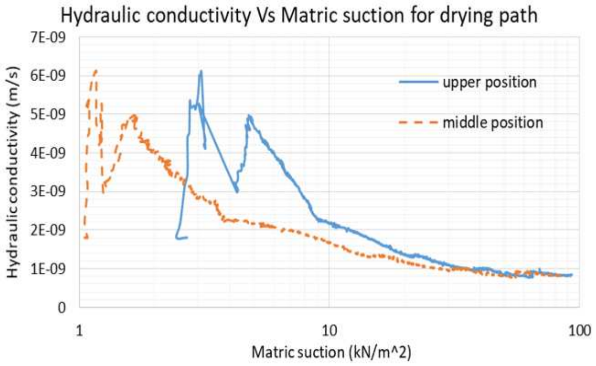

Figure 9. Variation of hydraulic conductivity with matric suction during drying path.

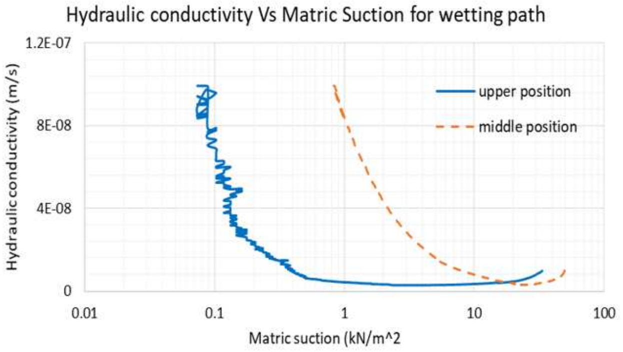

Figure 10. Variation of hydraulic conductivity with matric suction during wetting path.

6 DESTABLISHMENT OF SOIL WATER CHARACTERISTIC CURVE (SWCC)

The SWCC for a soil is defined as the relationship between water content (soil wetness) and matric suction for the soil. As previously outlined, SWCC is required as a key property for advanced analysis of slope behaviour including infiltration, and prediction of unsaturated shear strength.

Degree of saturation (S_r), gravimetric water content (w) or volumetric water content (Θ) and void ratio (e) are all related by the Equation:

$$\theta = \frac{v_w}{v} = \frac{wG_s}{1+e} = \frac{S_r e}{1+e} \tag{6}$$

6.1 *SWCC using KU Tensiometer*

During this method, sample is gradually wetted and dried and their suctions were monitored continuously. The sample's weight was also continuously measured. Specifics of this method are discussed in the Section 5 and SWCC obtained for both drying and wetting path analyses are given in Figure 12. With the KU tensiometers, matric suction values achievable was limited to 100 KN/m^2.

6.2 *SWCC using Pressure plate apparatus*

SWCC was established alternatively using a 5 bar pressure plate apparatus. Four compacted soil samples were placed on the high air entry disc and saturated. Filter papers were placed between soil samples and the disc to prevent adhering of wet soil to the disc. Mass of soil adhering to the filter paper could be obtained. After saturation, a predetermined value of air pressure was applied to bring the specimen to equilibrium under a matric suction. During the process water gets released from the specimen and the pressure was maintained until the flow of water ceased.

The mass of the sample at the equilibrium state was determined to compute the volumetric water content corresponding to the maintained matric suction. Matric suction values greater than 100 KN/m^2, up to 250 KN/m^2 was achieved with pressure plate apparatus. The special feature to be noted is that the moisture content change corresponding to the matric suction change from 0 to 100 KN/m^2 is quite small.

6.3 *SWCC using Gradation curve*

A distinguished physico-empirical model proposed by Arya and Paris (1981) was used to predict the volumetric water content- matric 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 formulation is based on an empirical parameter, α used to fit the experimental results to the model. The relationship between volumetric water content and matric suction from all the other methods have been used to calculate the empirical model parameter, for each soil type as presented in Figure 11. The SWCC derived by this technique is also presented in Figure 12.

The experimentally determined SWCCs presented in Figure 12 are in a similar range. A matric suction change of 0-100 KN/m^2 had been achieved with a volumetric water content change of only about 5% in the SWCC obtained from pressure plate apparatus and continuous measurement method. But in the SWCC curve estimated from the grain size distribution, the corresponding water content change is much larger.

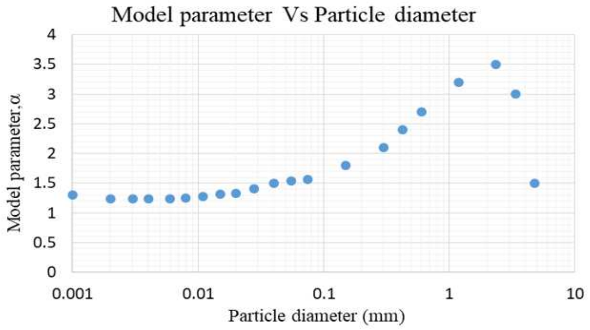

Figure 11. Variation of model parameter with particle diameter.

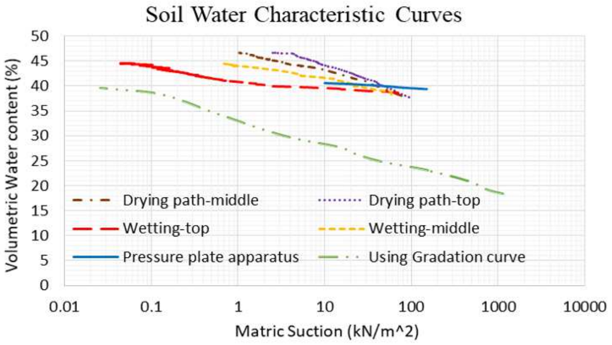

Figure 12. Variation of volumetric water content with matric suction.

7 SUMMARY AND CONCLUSIONS

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 a 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.

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 the analytical studies done by Sujeevan and Kulathilaka (2011). The findings of these analytical studies highlighted the importance of establishing these basic characteristics for Sri Lankan residual soils.

The residual soil for the study was obtained from a natural slope in the premises of University of Moratuwa. Tests were commenced using modified direct shear apparatus incorporated with a KU tensiometer, to determine the strength characteristics of unsaturated soils.

The miniature tensiometer used in this study was of a lower capacity, capable of measuring suction from value of zero to 100 kPa. This smaller range of suction is however more appropriate for slope stability studies.

A suction-monitored direct shear box equipped with the miniature tensiometer was used to determine the shear strength characteristics of unsaturated soils. Different levels of saturation were obtained by placing specimen of compacted samples in the pressure plate apparatus and bringing to equilibrium under a predetermined matric suction.

Although equilibrium stage was achieved before applying the normal load, during consolidation stage, the equilibrium matric suction appeared to have changed. Changes were greater at higher consolidation loads.

Variation of the apparent cohesion with the matric suction was plotted. These plots demonstrated that the ϕ^b value is not a constant as observed by other researchers.

SWCC was determined using pressure plate apparatus and estimated using the grading curve based on the Arya and Paris (1981) method. The SWCCs determined by different experimental techniques are in a similar range. But the SWCC derived from Arya and Paris method has deviated from the experimental curves.

The difference of the wetting SWCCs obtained from continuous wetting method appear to be greater than that of drying SWCCs. This is believed to be due to the greater non-linearity of the suction distribution due to poor infiltration which depends on dry density, structural arrangement of soil particles, mineral composition and crack pattern developed on the top surface of the soil specimen and soil type.

The SWCCs as well as the permeability function were determined for both wetting and drying paths using continuous measurement method. The advantage of this method is that the SWCC and permeability function of an undisturbed sample can be determined in the suction range of 0 KN/m^2 to 100 KN/m^2 within less than a week.

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