Unsaturated Soil Testing for Slope Studies

Jotisankasa, A., Tapparnich, J., Booncharoenpanich, P., Hunsachainan, N. & Soralump, S.
Geotechnical Engineering Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok

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ABSTRACT: Slope failure in tropical climate frequently occurs in the ground of the vadose zone with deep ground water table. Unsaturated soil properties are thus required in many advanced analyses related to stability and infiltration. This paper reports on laboratory testing technique used to characterize unsaturated soil properties for slope stability studies, currently used at Department of Civil Engineering, Kasetsart University. The methods principally employ miniature tensiometers and psychrometers for direct suction measurement during testing. The relationship between the additional cohesion and suction was determined in the suction-monitored direct shear box. The soil-water characteristic curves as well as the permeability suction function were investigated on undisturbed samples for both wetting and drying paths. The method is based on continuously drying and wetting the soil sample while continuous monitoring the suction gradient and the change in soil mass. The advantage of this method is evident in terms of cost and time associated. Some test results based on these techniques are then shown for a variety of soils in Thailand with some preliminary application on slope stability.

1 INTRODUCTION

Slope failure in tropical climate frequently occurs in the ground of the vadose zone with deep ground water table. These tropical slopes are generally unsaturated at most time of the year and the pore water pressure is negative. This negative pore water pressure or suction contributes to additional shear strength of soil and the stability of the slope (Fredlund & Rahardjo, 1993).

Nevertheless, prolonged rainfall and infiltration can diminish soil suction to nearly zero at a critical depth and frequently become a triggering mechanism of shallow slope failure (e.g. Springman et al., 2003, Chen et al., 2004, and Godt et al., 2009). Additionally, perched water table or positive pore water pressure can also be induced during heavy rainfall at a shallow depth in soil slopes as a result of wetting front being impeded by zones of much lower permeability in drier unsaturated soil or impervious rock underneath (e.g. Vaughan, 1985, Collins & Znidarcic, 2004, and Jotisankasa et al., 2008).

In order to understand the rainfall-induced landslide mechanism, many researchers have incorporated unsaturated soil properties into slope stability and infiltration analysis. Lu & Godt (2008), for example, based on infinite slope stability analysis with analytical 1-D steady unsaturated seepage calculation, showed their prediction of slope instability is consistent with actual shallow failure in the field which cannot be predicted by the classical infinite slope theory. Collins & Znidarcic (2004), using a similar approach with finite element transient seepage calculation, found that fine-grained soils and infiltration rates in order of 10^{-5} m/s or 1300 m/day do not lead to the development of positive pore pressure. In this case, failure will more often occur due to the decrease in shear strength caused by the loss of suction and not due to the development of positive pressure.

Other researchers such as Ng & Shi (2003) and Rahardjo et al. (2007), employing a similar approach, highlighted the importance of antecedent rainfalls and soil permeability on slope stability. More advanced coupled Finite Element stress-strain and seepage analyses considering unsaturated properties have also been increasingly used to predict the variation with time of deformation for shallow slope failure (e.g. Smith et al., 2002, Alonso et al. 2003, and Sasahara et al. 2008). This type of analysis has been used as a basis in an early warning system for landslide, as suggested by Baum et al. (2008) Bao & Ng (2000) as well as Mairaing et al. (2009).

All these research efforts emphasize the importance of understanding unsaturated soil behaviour in slope stability studies and especially in the investigation of infiltration process. This paper thus describes some laboratory tests developed and performed at Department of Civil Engineering, Kasetsart University in order to investigate unsaturated soil behaviour for slope stability studies in Thailand.

2 SUCTION MEASUREMENT

As stated previously, the tropical slopes are normally unsaturated and the pore water pressure is of negative value. This negative pore water pressure, or the tensile stress in soil water, is also referred to as the matric suction, s,

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

where u_a is the pore air pressure (equal to zero at atmospheric condition) and u_w is the pore water pressure. There are a variety of methods for measurement of matric suction such as axis-translation, tensiometer, filter paper etc (Fredlund & Rahardjo, 1993, Ridley et al., 2003). At Department of Civil Engineering, Kasetsart University (KU), a miniature tensiometer was developed consisting of 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 details by Jotisankasa (2010). Typical results of matric suction measurement on a carefully sealed soil sample are shown in Figure 2a.

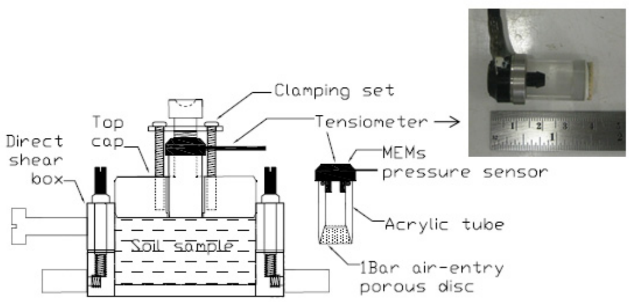

Figure 1: KU-tensiometer and its incorporation in direct shear box (modified from Jotisankasa and Mairaing, 2010).

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.

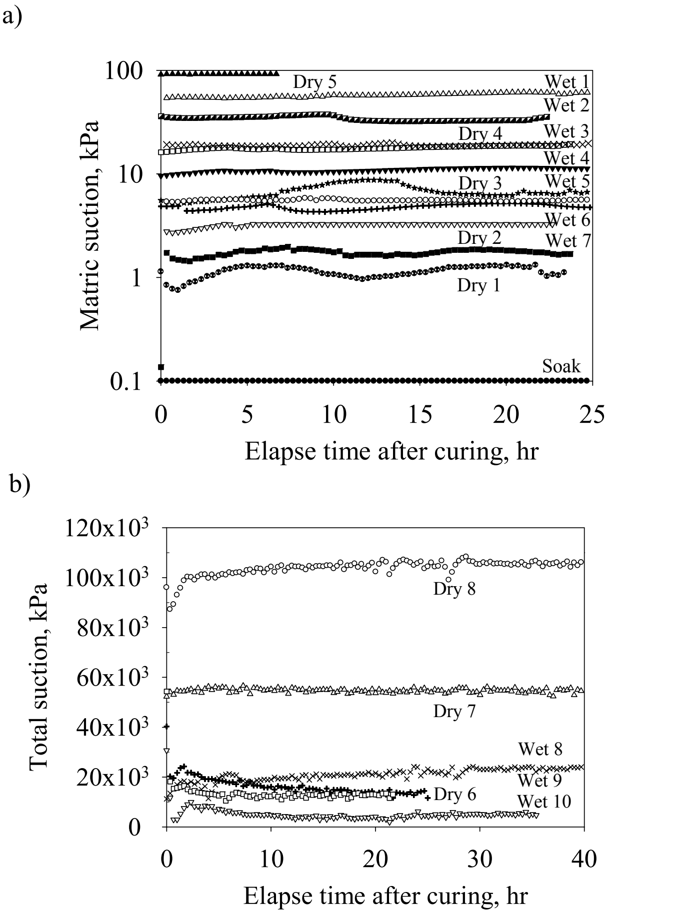

Figure 2: Typical results during measurement of (a) matric suction using tensiometer; (b) total suction using a relative humidity sensor (Tapparnich, 2010).

In the slope stability study, rain infiltration and evaporation process is frequently investigated in order to couple the climatic effect with the stability analysis. The boundary condition at the ground surface is of great importance when performing such analysis (Vaughan, 1994, Rahardjo et al., 2009). The value of suction at this boundary in general undergoes an extreme fluctuation during wet and dry season. In particular, it can exceed many thousands of kPa after a prolonged dry period. At such high suction, it is generally not possible to measure the matric suction, and therefore the total suction, ψ, is monitored instead. The total suction is defined as the total affinity that a soil has for water, or the sum between the matric suction and the osmotic suction, which is due to the presence of salt solution in soil water. The total suction is related to the relative humidity of the ambient air close to the soil by the relationship

$$\psi = -\left[\frac{RT}{V_{mol}}\right] \cdot \ln(R_h) \tag{2}$$

where R_h is the relative humidity, R is the universal gas constant (8.314 $J.mol^{-1}.K^{-1}$), V_{mol} is the molecular volume of water vapour (0.01802 m^3), and T the absolute temperature (^oK).

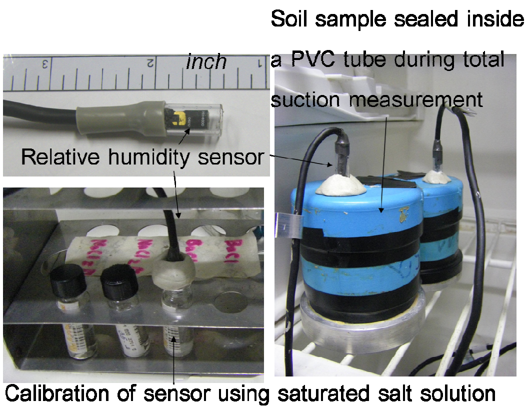

Figure 3: Relative humidity sensor, its calibration and its use for total suction measurement.

Table 1: Properties of the saturated salt solution used for calibration of the relative humidity sensor. (Modified from Lu & Likos, 2004).

Saturated salt solution	Temperature (°C)	% Relative Humidity at 25°C	Total suction, kPa	d(RH)/dT (from 25°C)
$NaOH.H_2O$	15-25	7	365,183	0
NaCl	5-60	75.1	39,323	-0.02
KCl	5-40	84.2	23,617	-0.16
$BaCl_2.2H_2O$	5-60	90.3	14,012	-0.08
H_2O (Distilled water)	-	0	0	-

Figure 3 shows the relative humidity sensor used in this study for measurement of total suction. The device is the Honeywell polymer capacitive RH sensor encased in an open-end transparent tube, calibrated using salt solution and used within a temperature controlled chamber (20±0.5°C). Table 1 describes the properties of the salt solutions used for calibration of the device. During measurement, it is important for the relative humidity within the space in front of the sensor to reach equilibrium with the soil air. Normally, a period of two days or longer is allowed for the equilibration of the total suction. Figure 2b shows example of the equilibration time required during the measurement of total suction. It can be seen that much longer equilibration period is required for the total suction measurement (2-4 days) than it is required for the matric suction (less than 1 day).

3 UNSATURATED SHEAR STRENGTH

One of the simplest relationships for shear strength in unsaturated soils is as follows;

$$\tau = c' + (\sigma - u_a)\cdot \tan\phi' + c^s \tag{3}$$

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

$$c^s = (u_a - u_w)\tan\phi' \qquad \text{if } u_w > u_a$$

$$c^s = (u_a - u_w)\tan\phi^b = (u_a - u_w)\chi\tan\phi' \qquad \text{if } u_w < u_a \tag{4}$$

where u_w = pore water pressure, ϕ^b = angle of shearing resistance due to suction, χ = Bishop's parameter which can be approximate to degree of saturation.

Jotisankasa & Mairaing (2010) studied the relationship between c^s and suction of residual soils from landslide areas using the suction-monitored direct shear test as shown in Figure 1. 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. This testing technique was in fact similar to those presented by Tarantino & Tombolato (2005) and Jotisankasa et al. (2007b). 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 90 kPa. This smaller range of suction is however more appropriate for slope stability study.

During testing, a constant water content condition of the soil specimen is maintained by using plastic wrap and pieces of wet clothes to cover the whole shear box. With this technique, the water contents before and after testing were found to differ only by 0-0.25% for a test period of about 8-10 hours (Jotisankasa & Mairaing, 2010).

Typical testing program for characterization of soils in slope stability studies at Kasetsart University 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 samples' moisture content were modified to the required values prior to testing by either gradual water spraying or air-drying.

Figure 4 shows typical behaviour during constant water content shearing of a compacted granitic residual soil mixed with 20% kaolin. These tests are part of a study on influence of kaolin percentage on shear strength of decomposed-granite silty soil mixed with the kaolin (Booncharoenpanich, 2010). The decomposed granite is classified as SM according to the Unified Soil Classification System. After mixed with 20% kaolin, the material became clayey sand, SC, with the plasticity index of 13.05%. The shearing rate in these direct shear tests was 0.05 mm/min and net normal stress was 15.5 kPa. At the initial shearing stage of most tests, some compression was observed which was accompanied by a slight decrease in matric suction (increase in pore water pressure). Subsequently, the sample with higher suction started to dilate and the suction increased accordingly. Upon reaching the peak and ultimate state, the suction then appeared to level off.

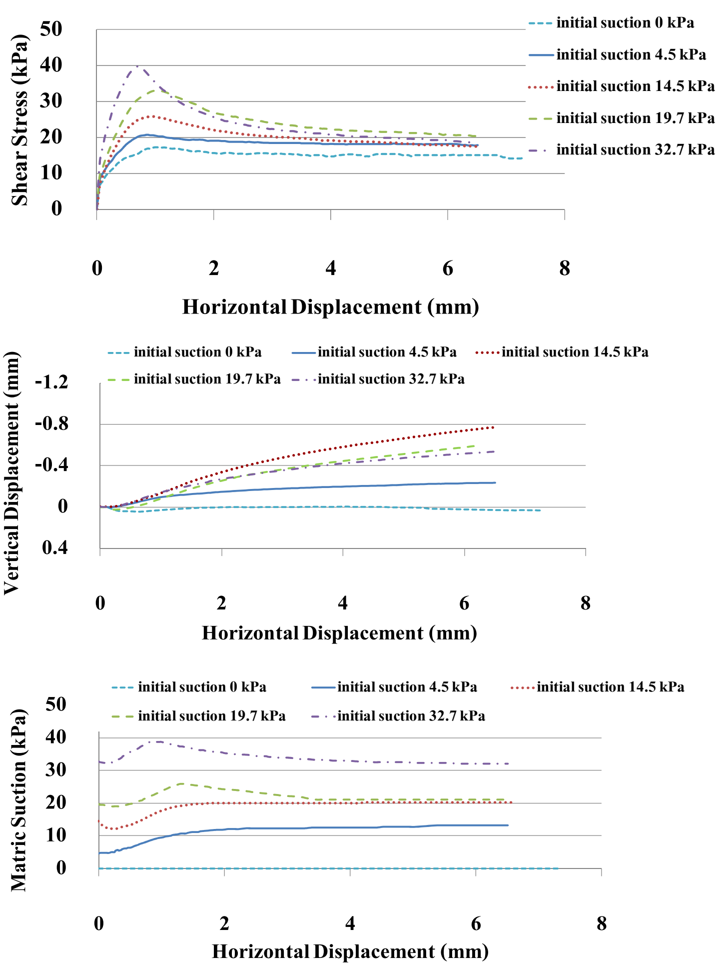

Figure 4: Typical results during constant-water content shearing in suction-monitored direct shear test on a compacted decomposed granite mixed with 20% kaolin.

This test programme has been followed for all decomposed granite-kaolin mixtures. Figure 5 shows the envelope of peak shear strength versus matric suction of the mixtures with different percentages of kaolin (0, 10, 15, 20%). The unsaturated shear strength of the mixture of 10%kaolin is the highest for the range of suction tested (0-45kPa) and thus this percentage of kaolin is the most suitable for soil improvement in terms of gain in unsaturated strength.

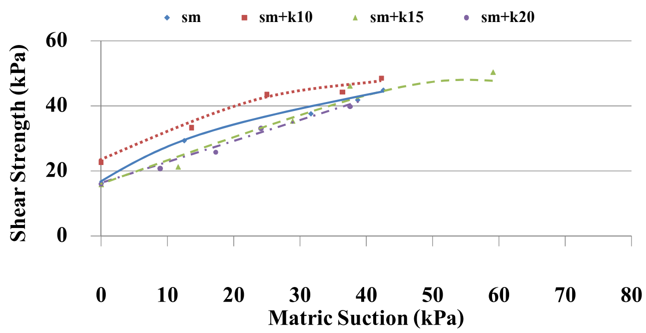

Figure 5: Peak shear strength versus matric suction envelope of decomposed granite (SM) mixed with different percentages of kaolin (0, 10, 15, 20% by weight) at normal stress of 15.5 kPa.

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 (e.g. Brand, 1981, Rahardjo et al., 2009). For practical purpose, the conventional suction-monitored shearing tests was used in this study and thought to 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.

4 SOIL-WATER CHARACTERISTIC CURVE

The Soil-Water Characteristic Curve (SWCC), also called the Soil-Water Retention Curve, is a function, which describes the relationship between suction and the state of soil wetness. The soil wetness can be expressed in several ways, namely, degree of saturation, S_r, gravimetric water content, w, or volumetric water content, θ, which are all related by the equation,

$$\theta = \frac{w.G_s}{1+e} = \frac{S_r.e}{1+e} \tag{5}$$

SWCC is required as key properties for advanced analysis of slope including infiltration, and prediction of unsaturated shear strength. In addition, Johnson & Sitar (1990) and Jotisankasa & Vathananukij (2008) made use of the SWCC in order to estimate the amount of rainfall required to reduce the suction to zero or saturate the slope, which is used as basis for early warning system for shallow landslide.

Various methods can be used to determine SWCC such as axis translation, filter paper, tensiometer, chilled-mirror hygrometer etc. In this study, SWCC of intact undisturbed sample is determined using miniature KU tensiometer and relative humidity sensor as shown in Figure 3. Two main testing methods are currently used. The first one is the *point-wise measurement* method, by which the sample is gradually wetted and dried and their suctions during each stage were monitored incrementally. A minimum curing period of about 2-3 days between each increment was allowed for equilibration of the suction throughout the sample, which was carefully wrapped to prevent evaporation.

The second method is called *continuous measurement.* For the drying SWCC, the top surface of soil sample was left exposed to ambient air, and the soil suction was monitored continuously at three locations on sample's side as shown in Figure 6. The sample's weight was also continuously measured using an electric balance connected to a datalogger. Typical results of such tests on silty residual soil from sedimentary rock (mudstone/siltstone) from Laplae, Uttaradit province are shown in Figure 7. It can be seen that during drying, the suction across the sample did not differ by more than 20%. As shown in Figure 8, the drying SWCCs from both methods are in a good agreement.

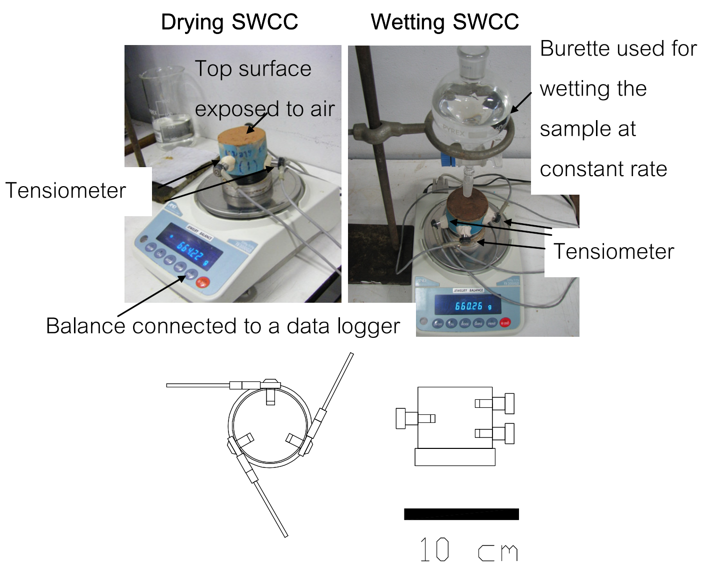

Figure 6: Experiment setup for the continuous measurement of SWCC.

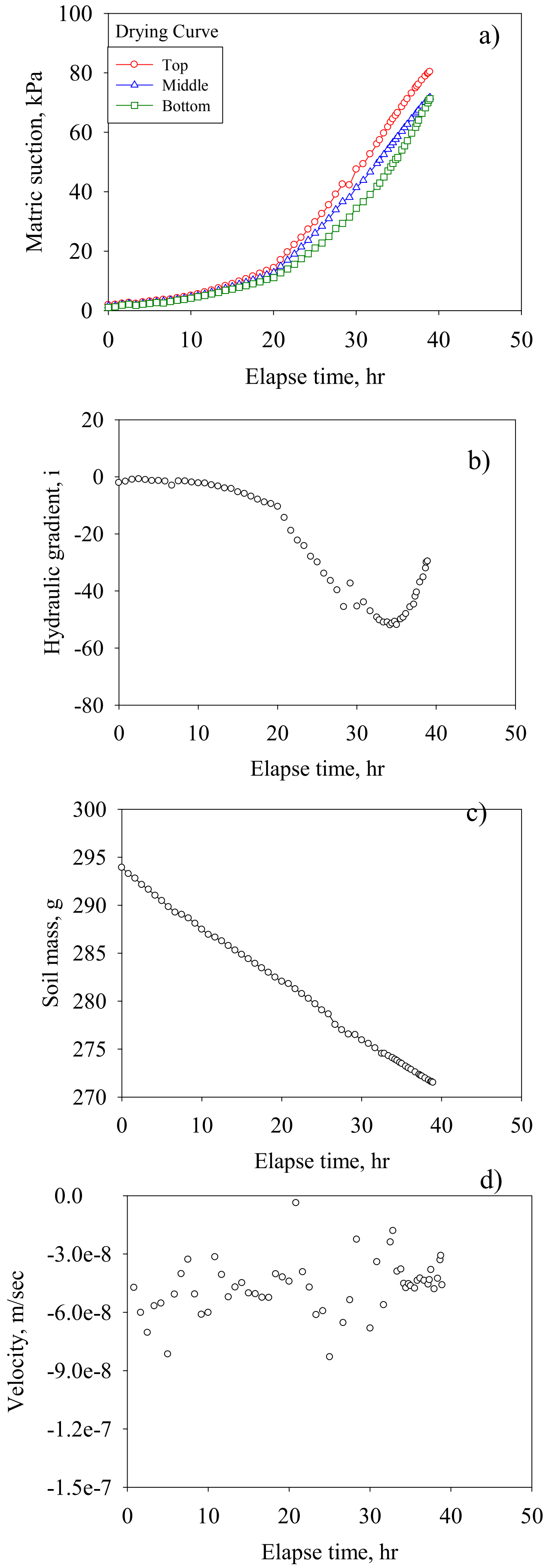

Figure 7: Typical results during drying path of continuous SWCC measurement of a silty residual soil.

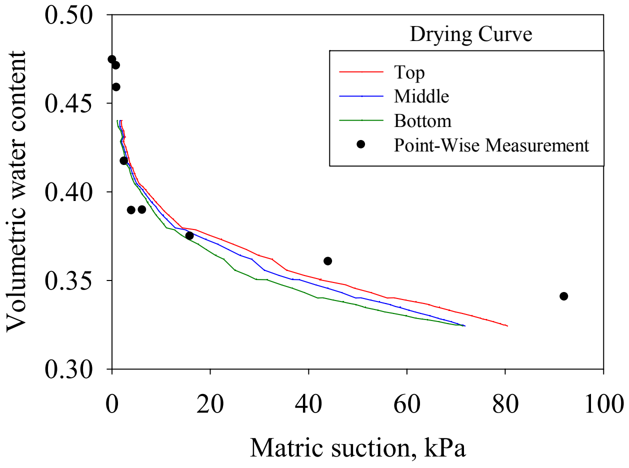

Figure 8: Drying SWCCs from continuous and point-wise measurement methods of a silty residual soil

For the determination of wetting SWCC, the top surface of sample is continuously wetted by way of water dripping from burette as shown in Figure 6. Typical results on the same material are shown in Figure 9.

Wetting SWCCs as determined using the continuous measurement method and pointwise measurement method are shown in Figure 10. The difference of the wetting SWCCs from the two 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.

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 90 to zero kPa). Besides, the function of permeability at different suctions, and water contents can also be determined from this test as described in the following section.

5 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 & Likos (2004) gives an overview of different techniques used to determine permeability function.

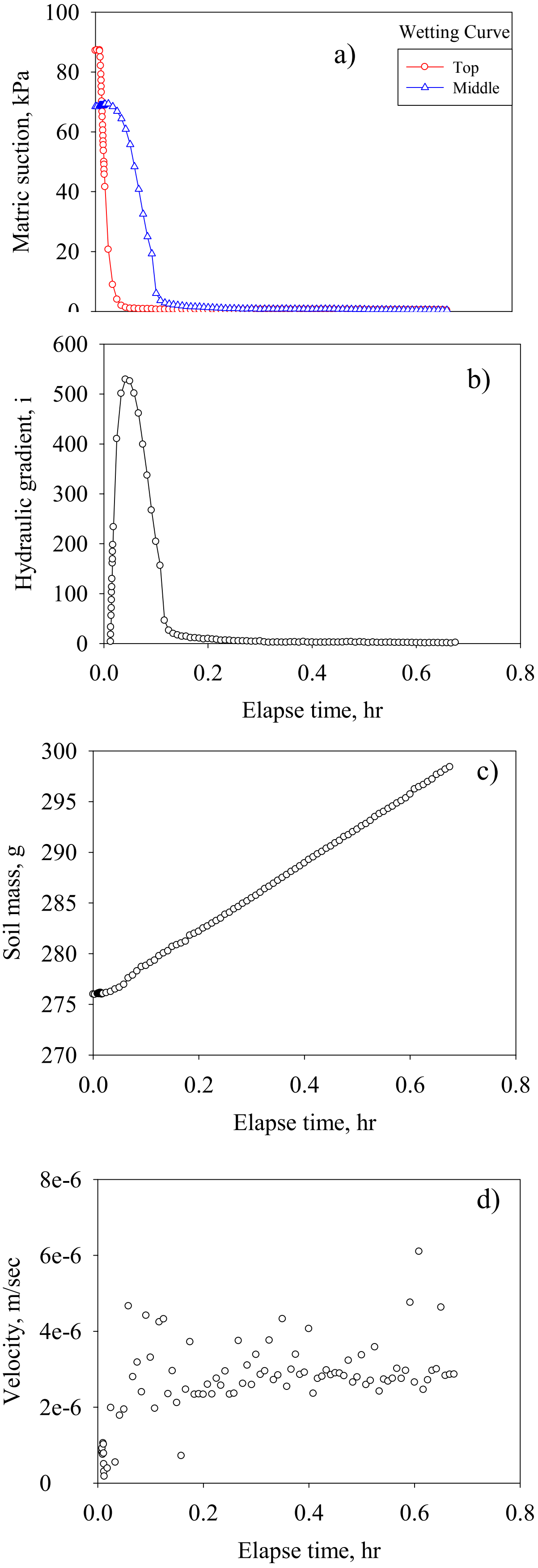

Figure 9: Typical results during wetting path of continuous SWCC measurement of a silty residual soil.

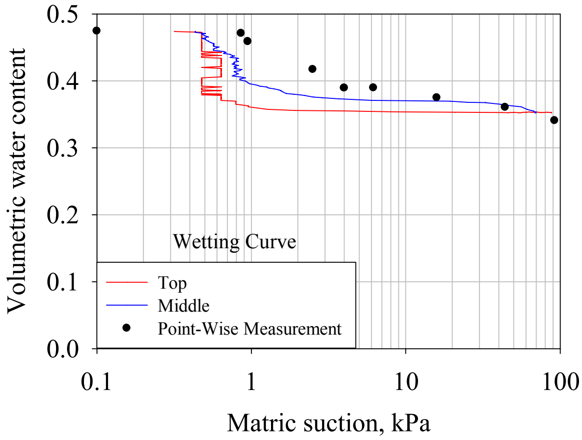

Figure 10: Wetting SWCCs from continuous measurement and point- wise measurement of a silty residual soil.

The aforementioned continuous SWCC measurement method can also be used to determine the permeability function. As shown in Figure 6, 7a, 8b, the values of suction at three locations can be used to calculate the hydraulic gradient, i, as follows;

$$i = \frac{d(z - s/\gamma_w)}{dz} \tag{6}$$

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 test, the value of hydraulic gradient, i, is calculated using linear regression over the three tensiometer measurements. For the wetting test, experience suggests that the gradient, i, calculated over only the upper and middle pore pressure measurement gives a better results of k-function than if calculated over three measurements. This is perhaps due to non-uniformity of the pore water pressure distribution as described previously. As shown in Figures 7b, and 9b, i appears to vary nonlinearly with time. The negative value of i suggests upward movement of water or net evaporation.

The plot of change in soil mass with time, as shown in Figures 7c, and 9c, are used to calculate the flux or discharge velocity, v, at any particular time as follows;

$$v = \frac{dV_w}{A \cdot dt} \tag{7}$$

where dV_w is the change of volume of water in soil sample calculated from change in soil mass during test, A is the cross section area of sample, and t is the elapse time. Linear regression is used to calculate the slope (velocity) over 30 data points. The value of permeability at any suction and volumetric water content can then be calculated as in Eq (8).

$$k = \frac{v}{i} \tag{8}$$

Permeability functions determined by this method are shown in Figure 11. Both wetting and drying k-functions appear to be in the same range. 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 continuous technique thus offer a very quick and simple way for k-function determination of unsaturated soils

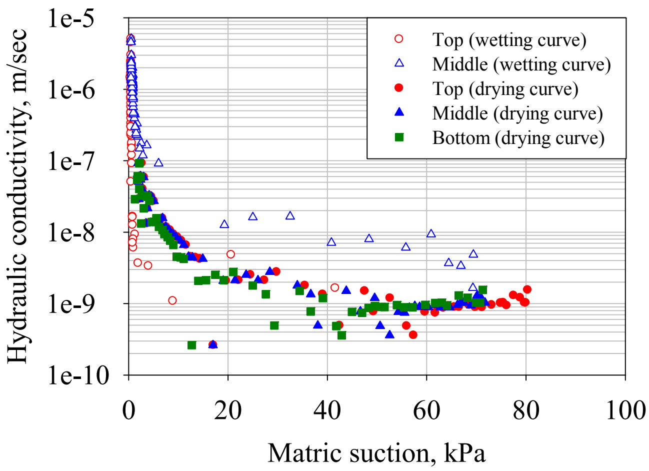

Figure 11: Permeability functions determined from continuous SWCC measurement.

6 APPLICATIONS

In order to illustrate some basic applications of the unsaturated properties for slope studies, the safety factor of infinite slope is calculated as shown in Figure 12. The shear strength parameters of compacted granitic soil, mixed with different percentages of kaolin are used in the analysis. The factor of safety, F, is calculated as follows;

$$F = \frac{c' + (\gamma \cdot z \cos^2 \beta) \cdot \tan \phi' + c^s}{\gamma \cdot z \sin \beta \cdot \cos \beta} \tag{9}$$

where the hypothetical slopes with depth of failure, z = 1m, and slope gradient, β = 42 degrees, and unit weight, γ= 19 to 20 kN/m^3 were analyzed. The value of c^s is calculated using Eq (4), as determined from the direct shear box (Figure 5) and also estimated using the Eq (10)

$$c^s = (u_a - u_w)\frac{\theta_{33}}{\theta_s}\tan\phi' \qquad ;\text{if } u_w < u_a \tag{10}$$

where, θ_s = saturated volumetric water content, and θ_{33} is the volumetric water content at 33 kPa suction or at the nominal field capacity (Jotisankasa & Mairaing, 2010).

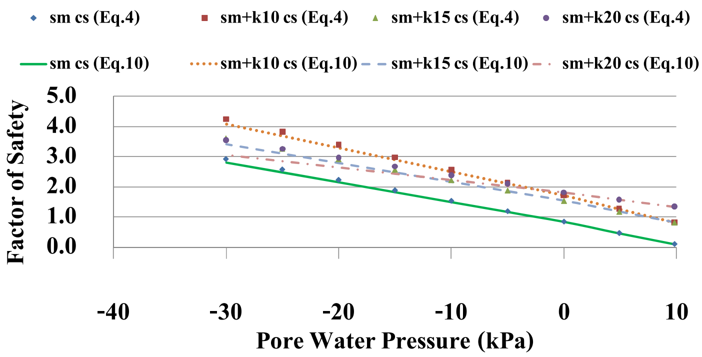

Figure 12: Variation between factors of safety and pore water pressure.

It can be seen that the estimation of unsaturated strength using field capacity (Equation 10) gives a satisfactory results if compared with the experimental test results from direct shear test (Equation 4) with less than 14% difference in Factor of Safety. This method of estimation using Eq (10) is very useful if there are not enough samples for shearing test and only the data of field capacity and porosity is available.

Another interesting trend is that the pore water pressure at failure (when Factor of Safety =1) of the decomposed granite (SM) slope without kaolin mixture is about -3kPa: a negative value. However if the decomposed granite is mixed with kaolin the value of pore water pressure at failure is about +8 kPa or more: a positive value. The value of suction thus seems to be significant for maintaining slope stability in the case of completely decomposed granite compacted without any soil improvement.

7 CONCLUSIONS

Slope instability in the tropics frequently occurs in the ground with deep water table. In this study, the testing methods for unsaturated soils principally employ miniature tensiometers and psychrometers for direct suction measurement during testing. The relationship between the additional cohesion and suction was determined in the suction-monitored direct shear box for decomposed granite mixed with kaolin. The mixture of 10% kaolin appears to have the highest unsaturated strength.

The soil-water characteristic curves as well as the permeability-suction function were investigated on residual soil from sedimentary rock for both wetting and drying paths. A novel method proposed is based on continuously drying and wetting the soil sample while continuous monitoring the suction gradient and the change in soil mass. 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 90 kPa within less than a week.

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