IMPORTANCE OF UNSATURATED SOIL MECHANICS IN GEOTECHNICAL ENGINEERING IN THAILAND

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บทคัดย่อ : บทความนี้แนะนำสาขาวิชากลศาสตร์สำหรับดินไม่ชุ่มน้ำ พร้อมด้วยตัวอย่างการนำไปใช้ประโยชน์แก้ปัญหาทางวิศวกรรมปฐพีกลศาสตร์และธรณีสิ่งแวดล้อม อีกทั้งได้เน้นถึงความเข้าใจในกลไกที่ทำให้เกิดแรงดูด (suction) ในดินและการตรวจวัดแรงดูดนี้ นอกจากนี้ยังได้สรุปแบบจำลองทางคณิตศาสตร์ที่ใช้อธิบายพฤติกรรมของดินไม่ชุ่มน้ำที่ได้รายงานในบทความอื่นๆ บทความนี้ยังได้เสนอกรณีตัวอย่างของการวัดค่าความเปลี่ยนแปลงของกำลังของดินกับค่า suction ของดินบริเวณแผ่นดินถล่มที่บ้านน้ำก้อจังหวัดเพชรบูรณ์

ABSTRACT : This paper presents an introduction to unsaturated soil mechanics and some examples of its application for some geotechnical and geo-environmental problems in Thailand. The importance of understanding the mechanism underlying suction and its measurement is highlighted. Also reviewed is the state-of-the-art modelling of unsaturated soil behaviour. A case study is described of the measurement of variation of strength with suction for a saprolitic soil from a landslide site in Petchaboon, Thailand.

KEYWORDS : Unsaturated soils, Suction, Constitutive models , Rainfall-induced landslide, Collapsible soils

1. Introduction

A large number of engineering problems in Thailand are associated with unsaturated soils. One of the most common problems is that of collapse of materials such as loess, or loosely compacted fills, which can undergo large settlements as they are wetted at relatively large stresses (e.g. [1], [2], [3]). In many hillslope areas of Thailand, rainfall-induced landslides normally occurring as shallow movements in an unsaturated zone, are one of major causes of economic and social loss, [4]. Even though natural soils are largely fully saturated in the areas where ground water level is high such as central Thailand, compacted fills, used in man made structures such as earth dams, road subgrades, and embankments, are placed in an unsaturated state.

In addition to traditional geotechnical engineering, geoenvironmental problems, such as contaminant transport, leachate and gas migration from landfill or other contaminated sites, usually take place within the vadose zone where soils are largely unsaturated. Compacted liners for waste disposal facilities are also normally placed in an unsaturated state. For example, dessication cracking of the unsaturated liners can seriously impair the performance of the landfill and results in groundwater contamination, e.g. [5].

A sound understanding of the mechanical and hydraulics behaviour of this type of material is thus required, in order that safe and cost-effective solutions to engineering problems related to such materials can be arrived at. This paper presents the background of the subject, including the mechanisms controlling soil suction, and modelling of unsaturated soils, as well as a case study of the measurement of variation of strength with suction for a saprolitic soil from a landslide site in Petchaboon, Thailand.

2. Soil suction

2.1 Physics for soil suction

Soil suction can be described as the potential of the soil for water attraction. It is the key variable that governs the mechanical behaviour of unsaturated soils as well as the flow regime within the soils. Soils above the groundwater table have an affinity for water, which, either partially or fully, fills in the space within the soil pores. This soil water above the groundwater table is normally under a tensile stress or a negative pore water pressure. This tensile stress, measured through a porous tip making an intimate contact with the soil water, is known as the matrix suction, *s*. Matrix suction is defined as the excess of pore air pressure, u_a, over pore water pressure, u_w.

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

The matrix suction is caused by the two main physical phenomena, namely the capillarity and the surface adsorption. The capillarity phenomenon is directly related to the surface tension of water, as illustrated in Figure 1a. The surface adsorption is principally relevant to clay minerals and occurs as a result of the clay particles' negatively charged surfaces (Figure 1b).

Another way of expressing the affinity that a soil has for water is through the relative humidity of the ambient air close to the soil. This affinity is called the total suction, ψ, which by definition, is the stress required to remove a water molecule from the soil into the vapour phase. The total suction is related to the relative humidity by the relationship,

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

where Rh is the relative humidity, which equals the ratio between the partial pressure of the vapour and the saturated vapour pressure of the soil air (P/P_0), 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 (^{o}K).

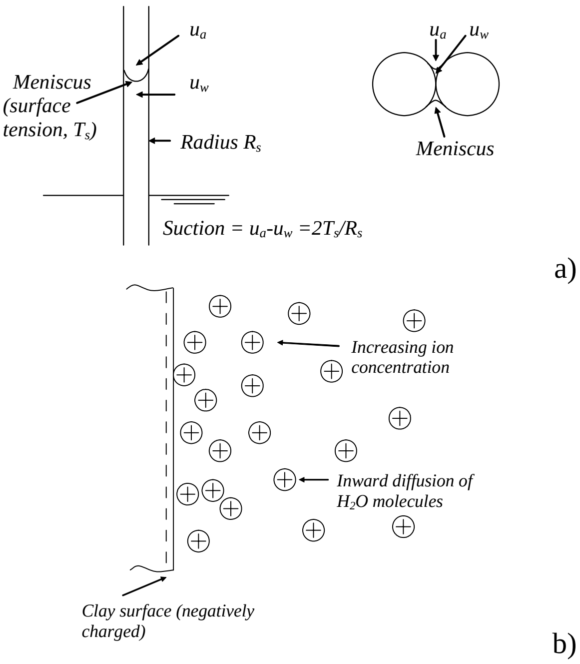

Figure 1 The two phenomena contributing to the matrix suction; a) capillarity; and b) water adsorptions by a clay particle surface.

The total suction is the sum of the matrix suction, *s*, and the osmotic suction, π. The osmotic suction is a function of the concentration of dissolved salts within the soil water, whose presence gives rise to some additional affinity for water of the soil. In general, it is the total suction that governs the flow within unsaturated soils. As an example, provided that other potentials are the same, any gradient in the concentration of dissolved salts within soil water, or in the osmotic suction, can cause flow of water in a soil. Thus this is of geo-environmental significance, especially since flow can be driven by contaminant concentration gradients. In addition, the water content of a soil in contact with the atmosphere is determined by the total suction, which corresponds to the atmospheric humidity.

However, it is normally considered that the strength of an unsaturated soil is determined by the matrix suction, even though any presence of salt within the soil water can cause some fundamental change in its mechanical behaviour [6]. Matrix suction and osmotic suction are generally considered as independent variables. In addition, thermodynamic considerations show that the total suction corresponding to zero water content is approximately 1000 MPa [7]. Engineers should not be surprised by the enormity of the suction value (1000MPa = 10000 atmospheric pressure), since the total suction is a measure of the potential or energy, and not the direct tensile stress measured in the laboratory.

2.2 Measurement of soil suction

Historically, the understanding of unsaturated soil mechanics lagged behind that of fully saturated soil, due in part to the lack of reliable suction measuring devices as well as the lack of their utilization in the field to gain more understanding of the problems. Ridley & Wray [8] categorise the suction measuring devices into two types; those that measure directly and others that measure indirectly. With direct measurement, the relevant quantity under scrutiny is measured, namely the pore water energy or tensile stress. The indirect measurements are ones that measure another parameter (e.g. relative humidity, resistivity, conductivity or moisture content), which are related to the suction through calibration relationships.

For both cases, they emphasize the importance for the engineer of knowing whether total or matrix suction is being measured. In general, if no contact is made between the measuring device and the soil water, the relative humidity of the ambient air within the soil is measured and so is the total suction. If the good contact is made between the soil water and the measuring device, and the concentration of dissolved salts can be assumed to be the same everywhere, the matrix suction is being measured. However at low degrees of saturation, the soil water might recede into the finer pores and become discontinuous, in which case it is normally difficult to guarantee that full contact is made and that the matrix suction is being measured.

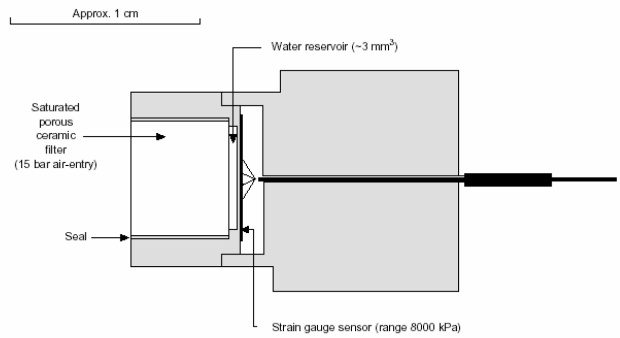

Figure 2 An Imperial College tensiometer or suction probe, Ridley & Burland, [9]

Figure 2 illustrated the Imperial college tensiometer, introduced by Ridley & Burland, [9]. The device was introduced to overcome the problem of bubble formation, or cavitaion, associated with conventional tensiometers when measuring suction above around 100kPa. The suction probe can measure matrix suctions up to about 1500kPa for relatively long periods (e.g. > 1 months). The design considerations for the probe include the optimisation of various components, namely a) the location of and type of the pressure sensor, b) the volume of the fluid reservoir c) the material from which the tensiometer is constructed and d) the pore size of the ceramic filter. In Section 4, some results of the unconfined compression tests carried out with this device will be shown to demonstrate its capability and application for rainfall-induced landslide problem in Thailand.

2.3 Soil-Water Retention surface

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

$$\theta = \frac{w.G_s}{1+e} = \frac{S_r.e}{1+e} \qquad (3)$$

The SWRC expressions have been adopted by geotechnical engineers for the prediction of various properties including shear strength, permeability, and thermal coefficient (e.g. [10]). However, the SWRC of a particular soil with a certain gradation curve is not necessarily a unique function in a space of, for example, Sr and log suction, but dependent upon many other factors, including hydraulics hysteresis, confining stress, as well as void ratios (see, e.g. [11]).

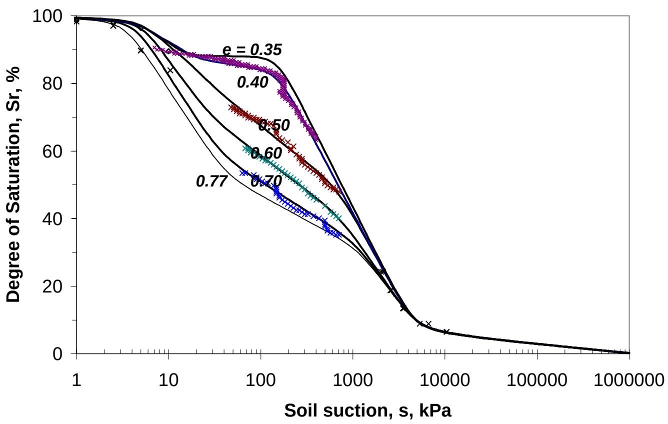

Figure 3 Contours of the main wetting surface for the compacted silty clay. The symbols indicate the processed data, Jotisankasa [11].

Figure 3 shows an example of the contours of SWRC during wetting at different void ratios based on a comprehensive studies by Jotisankasa [11] on a compacted silty clay using the suction probes incorporated within the suction-controlled triaxial apparatus, and the suction-monitored oedometer, as well as the filter paper technique,. As void ratio changes, the pore shape and their distribution within the soil change and so does the SWRC. The bimodality of the curves is also apparent. Therefore, care should be taken when adopting the uni-modal SWRC functions to predict other properties of the soil, and only the SWRCs should be used of the samples that correspond to the actual field situation in terms of confining stresses, void ratio, and fabric. The concept of 'Soil-Water Retention *Surface*' has been introduced by various researchers, such as Gallipoli et al. [12], and shown to represent better the soil-water retention behaviour, than does the 'Soil-Water Retention Curve'.

3. Modelling unsaturated soil behaviour

Modelling unsaturated soil behaviour have been the topics of research for several decades and a variety of approaches exist. Choices of the stress variables have also been a debatable area in unsaturated soil modelling.

The effective stress equations, which employ a single stress variable, have been proposed by various researchers. One of the most widely used relationship was that suggested by Bishop [13] as follows,

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad (4)$$

where σ is the total stress, and χ is a function of degree of saturation, S_r, varying from zero to one for 0 to 100% S_r respectively. The value of χ is estimated from shearing tests, by assuming the validity of the principle of effective stress. In general, this equation and others of this type are considered to be capable of successfully reproducing the shear strength of unsaturated soils

However, later studies, notably that by Jenning & Burland, [14] have shown that a single effective stress variable is not capable of completely describing partly saturated soil behaviour, especially the volumetric behaviour. Consider, for example, the case of a collapsible soil, loaded under a relatively high vertical pressure, and reducing in volume upon soaking the sample. According to the principle of effective stress, on wetting the sample to zero suction, its effective stress decreases due to decrease in suction and the increase in volume would be predicted. In most cases, however, for the collapsible soils the reduction in volume is observed.

Currently a general consensus is therefore that the net stress $(\sigma - u_a)$ and suction $(u_a - u_w)$ should be considered as independent variables, e.g. Wheeler & Karube [15].

3.1 Shear behaviour

Fredlund et al. [16] proposed that the shear strength of partly saturated soils can be expressed as an extension of the Mohr-Coulomb equation for fully saturated soils, as followed;

$$\tau = c' + (\sigma - u_a)\cdot\tan\phi' + (u_a - u_w)\cdot\tan\phi^b \qquad (5)$$

where c' and ϕ' are the effective cohesion intercept and friction angle for the soil in a fully saturated state, and ϕ^b is the friction angle with respect to changes in suction.

Early researchers had long been aware of the non-linearity of the relationship between the shear strength and suction. Bishop et al. [17] suggested that the χ factor of a soil, in Equation 4, is dependent upon a number of factors, including the degree of saturation, the moisture hysteretic state and the stress conditions. In other words, the angle ϕ^b in Equation 5 is not constant but changes with suction and could even become negative at high suctions, resulting in a decrease in the shear strength with suction.

The non-linearity of the shear strength-suction relationship can be explained qualitatively by a physical argument. For suctions below the air entry value, the degree of saturation is approximately unity and the influence of suction is equivalent to the applied stress. In this region, ϕ^b is equal to ϕ'. However, as the soil desaturates, the wetted contact area around the soil grains decreases and the contribution of suction to the shear strength reduces, resulting in a decrease in ϕ^b with suction. Gan & Fredlund [18] observed that the reduction in ϕ^b with suction is also influenced by dilation of the sample during shearing. For samples with higher dilation, such as those tested at low confining pressures, the reduction of ϕ^b with suction tends to be greater than those with lower dilation, for example tested at high confining pressure. Figure 4 illustrates this observation schematically in comparison with the corresponding SWRC.

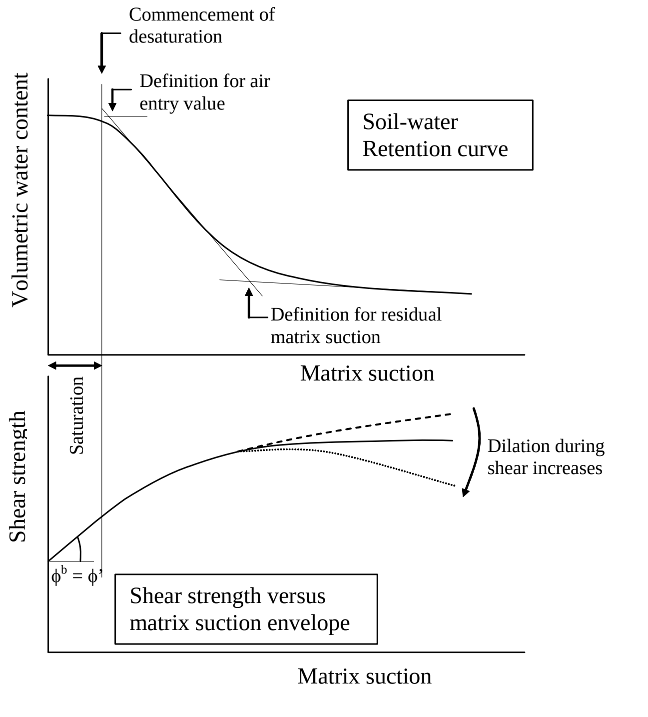

Figure 4 Schematic relationship between soil-water retention curve and shear strength versus matrix suction envelope, Gan & Fredlund, [18]

The angle ϕ' is normally assumed to be constant with suction. Toll & Ong, [19] & Jotisankasa [11] however found that ϕ' increases with decreasing degree of saturation, based on their results from triaxial tests on some tropical residual soils and a compacted silty clay.

Various researchers have proposed a number of models to describe the non-linear relationships of shear strength for unsaturated soils. Features of the Soil-Water Retention Curve, including the air entry value and residual suction, have been used in the formulation of these models. Vanapalli & Fredlund [20] provide a review of various procedures.

Once again, while this approach is particularly useful, it should be borne in mind that the SWRC for a soil is influenced by the change in pore structure resulting from changes in net stresses and void ratio, as well as by the hydraulic hysteresis. Only the SWRCs of samples, at appropriate confining pressures, having a similar hysteresis or wetting/drying history to the field conditions, should be used.

3.2 Volumetric behaviour

The volumetric behaviour of partly saturated soils could be defined as a function of separate stress variables, namely, net stress, and matrix suction. Figure 5 shows a typical state surface for such function. It can be seen in that the void ratio surface is warped indicating that wetting under a low applied load (AA') induces swelling, while wetting under high load (BB') involves collapse. The shape of the surface is dependent upon a number of factors including soil type, magnitude of applied pressure, the initial suction, void ratio and degree of saturation. In general, for sandy or silty soils, the void ratio at point A tends to approach that at A' due to its non-expansiveness. In Figure 5b, the relationship between Sr and suction can be seen to vary with net stress. This is particularly so for compressible soils as discussed in Section 2.3.

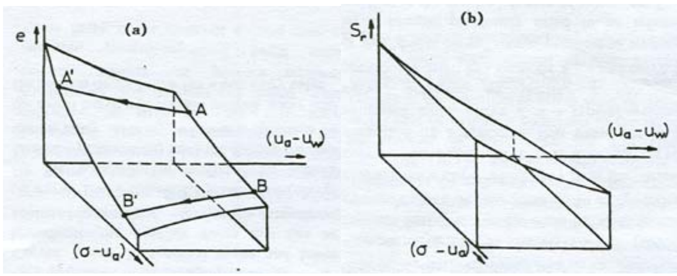

Figure 5 State surface concept for void ratio and degree of saturation, Wheeler & Karube [15]

The disadvantage of this concept however is that no distinction is made between recoverable and irrecoverable strains. In addition, the concept does not take into account the hydraulic hysteresis. The paths involving unloading or increasing in suction would lie below the state surface identified from loading or wetting. The uniqueness of the surface is thus only limited to those stress paths involving monotonic loading and monotonic change in suction.

Alonso, Gens & Hight [6] proposed a conceptual framework based on the theory of hardening plasticity in order to explain both the volumetric and shearing behaviour of partly saturated soils. Regarding the volumetric aspect, the framework is capable of predicting the non-uniqueness of the state surface by introducing several yield surfaces in the space of suction, net stress (mean, *p*, and deviatoric, *q*), and specific volume, $v = 1+e$. The first mathematical formulation of such concept was reported by Alonso et al. [21]. This model is particularly useful for predicting the collapse behaviour of non-expansive material and this is made possible by the introduction of the Loading-Collapse (LC) yield surface.

The Loading-Collapse (LC) yield surface, projected onto an s-(p-u_a) plot as the yield locus is shown in Figure 6, where p could represent either vertical stress for oedometric condition or mean stress $(\sigma_1+2\sigma_3)/3$, for triaxial condition. Irreversible compressive volumetric strains are predicted for any paths moving outside the locus with either an increase of (path L), decrease of s (path C) or both. Path L represents loading at constant suction, while path C represents wetting at constant net stress. For the region within the yield surface, elastic behaviour is predicted for both changes in suction and stress. Any decrease or increase in suction within the elastic zone induces reversible swelling or shrinkage respectively. The irreversible strain induced by path L will be equal to that induced by path C, which is related to the hardening parameter p_o^* . In other words the irreversible strains induced by both paths will be equivalent to compression along the Normal Compression Line at zero suction (fully saturated) from to p_{o1}^* to p_{o2}^* .

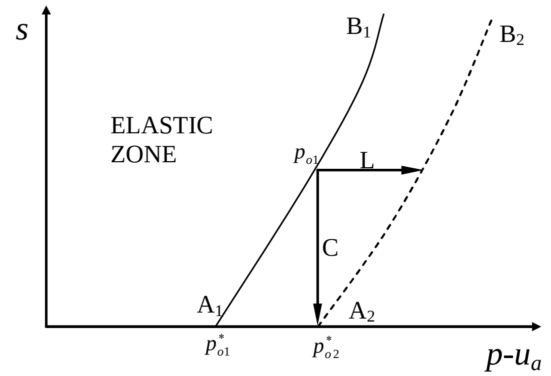

Figure 6 Loading-Collapse yield locus Alonso, Gens & Hight [6]

One of the fundamental assumptions of this model is the uniqueness of the LC surface, as identified by either loading and wetting. Jotisankasa [11] provides a detailed experimental investigation into this topic. In addition, despite the increasing use of this Alonso et al. type model, it is still incapable of reproducing many aspects of unsaturated soils.

In this respect, newer types of elasto-plastic models are proposed which are formulated in terms of two independent modified stress variables, see for example Wheeler & Karube [15], Wheeler et al. [22], and Gallipoli et al. [23]. These models incorporate the degree of saturation into the stress variables. They also consider separately the two mechanical functions of suction in the soil, that of stabilizing the soil grain, and that which is equivalent to the applied total stress, causing grain slippage. This new type of elasto-plastic models is capable of reproducing: a) an irreversible change of void ratio during wetting-drying cycle; b) a dependence of the response during virgin compression at constant suction on the previous history of suction ; c) a smooth transition from fully saturated to partly saturated behaviour. Although more powerful than the Alonso et al. type model, these newer elasto-plastic models ([22], [23]) are still in their early stage of development and still needs more experimental validation.

In summary, a variety of models explaining different aspects of unsaturated behaviour have been proposed. There are different levels of engineering problems, for which each type of these models are suitable. These models could potentially be used to help understand and solve various problems related to unsaturated soils in Thailand, e.g. collapse of loess and sandy soils in North Eastern region, rainfall-induced landslides, or shrinkage and swelling of compacted clay liners for landfills. More experimental research should be done to characterize the behaviour of these unsaturated soils of Thailand. In this respect, the accurate measurement of suction as well as other states, such as degree of saturation and water content, during the experiments are very important.

4. Suction-strength variation of a Saprolitic soil from Nam-Kor landslide

This section presents an example of such experiments with regards to rainfall-induced landslide problems. This landslide took place in Nam-Kor, Petchaboon in 2001 and involved numerous shallow slides with a depth of 1-2 meters, which subsequently accumulated into debris flow of tremendously destructive force. The saprolitic sandy clay was taken as a block sample from a typical site of these shallow slides by a team of Geotechnical Engineering Research and Development (GERD) center, Kasetsart University [4]. The block was taken at the depth of 0.7m from a pit located near the rear scarp of the slope.

A series of six suction-measured unconfined compression tests were carried out on 6 samples of Thai soil. The suction probe as shown in Figure 2 was attached to the unconfined sample during shearing and the suction was measured throughout the test.

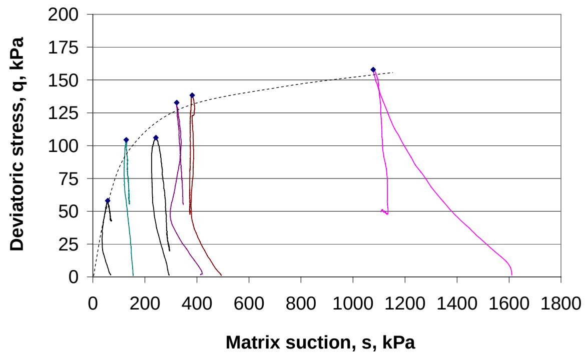

Figure 7 Results for unconfined compression tests on the Saprolitic sandy clay from Nam-Kor landslide

The results are shown in Figure 7 of deviatoric stress and suction during shearing for all 6 tests. The plot shows that suction-strength variation shown as dotted line is highly nonlinear. It is noted that the shear strength at zero suction is zero and there is no effective cohesion, $c' = 0$. This has simply been demonstrated by conducting slaking tests, (submerging in a beaker of water a sample, which later became fully disintegrated due to loss of suction), Atkinson [24]. A rapid reduction of shear strength can be noted when the suction reduces from about 200 to zero kPa. These results can be modelled using various approach stated above and incorporated into the rainfall simulation in order to determine the critical rainfall intensity and duration at which the landslide would be triggered.

5. Summary

The description of the mechanics of suction in soils and their measurement are summarised. A variety of approaches for modeling mechanical behaviour of unsaturated soils have been presented and the source of literature is given. Nevertheless, the topics of hydraulics and flow of water through unsaturated soils have not been touched upon due to the limited length of the paper.

The importance of unsaturated soil mechanics and the measurement of suction for solving some geotechnical problems in Thailand have been stated, with a particular reference to rainfall-induced landslide problem.

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