Influence of Soil Suction on Shear Strength of Residual Soils

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Saravanan Mariappan
Nexus EC Sdn. Bhd., Kuala Lumpur, Malaysia .

Faisal Hj. Ali
National Defence University of Malaysia

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Saravanan Mariappan , Faisal Haji Ali , Low Tian Huat
Civil Engineering Department, Universiti Malaya, Kuala Lumpur, Malaysia.

ABSTRACT

Weathered granite, sedimentary and metamorphic rocks are the main types of residual soil in Malaysia. In natural state the soil above ground water level are in unsaturated condition. Major parts of residual soils in Malaysia are in unsaturated state, therefore studies have to be done in order to understand the influence of soil suction on shear strength of these residual soils. Soil suction has important influences on water entry, structural stability, stiffness, shear strength and volume change, which is an important variable in soil engineering design.

Shear strength determination was carried out on unsaturated sample using specially modified apparatus. At the same time the concept of multistage triaxial and multistage multi suction is performed in order to eliminate soil variations. Discussion in the paper covers the modification of testing equipment, method of sample collection, details of multi stage test procedure and test results.

INTRODUCTION

Residual soils are product of the in-situ weathering of igneous, sedimentary and metamorphic rocks. They occur in most countries of the world but the greater areas and depths are normally found in tropical humid areas such as Malaysia. Residual soils in Malaysia mainly consist of weathered igneous or sedimentary rock. The interest of this research is to study the performance of shear strength of partially saturated weathered sedimentary residual soil. Total suction, water content and how they vary with time were the important variables in the research.

In order to have in depth study a model cut slope was adopted. Various soil samples were collected along the slope section in order to map out shear strength variation with respect to soil weathering grades. With the basic strength parameters, the influences of unsaturated soil mechanics were also studied to understand the behavior of soil with the changes of moisture content. **Figure 1** shows the cut slope layout with soil sampling locations. **Figure 2** indicates a map of weathering grades on the cut slope. Due to the variation in soil profiles, interest of this study were concentrated only on weathered sand stone material.

UNSATURATED SOILS

The principal and fundamental research on unsaturated soil mechanics started in 1962 by Jennings and Burland in Imperial College. At that time much interest was on Terzaghi's (1923) principle of effective stress for saturated soil which was proposed by him in the First International Conference on Soil Mechanics in 1936. The concept and research interest on unsaturated soil developed only in 1977. Fredlund and Morgenstern made the revitalization of unsaturated soil mechanics possible. Fredlund and Morgenstern introduced the third factor of $(u_a - u_w)$ into the earlier equation of effective stress defined as (Bishop, 1959):-

$$\sigma' = (\sigma - u_u) + X(u_a - u_w) \quad \text{-------- (1)}$$

Where σ' and σ are the effective and total stresses respectively, u_a is the pore air pressure and u_w is the pore water pressure. X is a function that depends on the saturation with value 1 to 100% and 0 for completely dry soil. The relationship between X and saturation was determined experimentally to evaluate the strength. τ, written in terms of stress state variables for an unsaturated soil and is an extension of equation used for saturated soils.

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

where:

c' = effective cohesion
σ = total stress
u_a = pore -air pressure
ϕ' = effective angle of internal friction
u_w = pore water pressure
$(u_a - u_w)$ = matric suction
ϕ^b = angle indicating the rate of increase in shear strength with respect to changes in $(u_a - u_w)$ when $(\sigma - u_a)$ is held constant.

The above equation assumes a planar failure envelope, the internal friction angle ϕ', remains essentially constant under saturated and unsaturated condition. The angle ϕ^b, which quantifies the effect of suction is measured from the τ Vs $(u_a - u_w)$ plot. The cohesion intercepts c_1, c_2 and c_3 due to the applied suction $(u_a - u_w)$ vary if the angle of internal friction ϕ' remains constant at different suction levels. **Figure 3.** shows the matric suction drawn on failure envelope.

SOIL WEATHERING GRADES

The residual soils at the slope were mapped for it's weathering grades. Boundaries between the weathered layers are not always clearly defined. Typically, a profile of residual soil will consist of three indistinctly divided zones as illustrated in **Figure 4**. The site geological map illustrates the estimated boundary of each weathering grade. The map also draws out the fault and soil boundaries. (Refer Figure 2.)

SOIL SAMPLE COLLECTION

Undisturbed block samples were collected from the site in boxes made of metal plates measuring 200x200x200 mm. After choosing a suitable location to sample, the topsoil of about 300mm was removed using lightweight shovels. Trenches were dug all around the soil mass of about 250x250x250mm. Sides of the soil mass are then trimmed slowly and carefully to fit the sample box size. The box was then fitted to the specimen with the bottom cap opened. The whole soil mass with the box in place were dug and removed. The top cover was placed and sealed with paraffin to prevent moisture lost. All the boxes were carried with care to the laboratory and kept in constant temperature humidified room.

SOIL SAMPLING

The sample from the block sample was removed using specially fabricated split-mould sampler. During extrusion of sample, silicon oil was applied to the sampler to reduce friction. During sampling the sampler was pushed into the block sample by using hydraulic jack, cutting it to the required diameter. The block sample container that is made of zinc plate allows elastic behavior reduces stresses in soil during extrusion. Finally the extruded sample will be cut to the required thickness. **Figure 5** illustrates the split sampler.

Four numbers of such split sampler will be pushed into the sample at the same time in order to obtain 4 soil samples. The samples will be used to perform two multistage of unsaturated soil test, one multistage CIU test and one for soil water characteristics curve. With this sampling method the effect of soil variation will be minimized.

TRIAXIAL TEST SETUP FOR UNSATURATED SOIL TEST

Bishop-Wesley triaxial cell set was modified to carry out the test on suction induced soil specimens. The top cap of the triaxial cell was modified to provide inlet for air pressure applied at the top of specimen. Suction was applied by controlling the pore air and pore water pressure. The layout of the modified triaxial setup is shown in **Figure 6**. Axis translation technique (Hilf, 1956) was used to apply soil suction to the specimens. A 15 bar high air entry disc was sealed on a modified base pedestal. This allowed the air and water pressures to be controlled during the application of deviator stress in order to maintain the constant matrix suction throughout the test.

Figure 6 : Triaxial

However, with time pore air may diffuse through the water in the high air entry discs and appear as air bubbles in the water compartment below the disc. Therefore the water compartment was fabricated to facilitate flushing of the diffused air bubbles on a periodic basis.

Figure 7 : DAVI

Diffused Air Volume Indicator (DAVI) was used to measure the amount of air that diffused through the ceramic disc and accumulated under ceramic disc. The recorded volume change during testing could indicate the suction equilibrium in the specimen. Suction equilibrium of the specimen can be determined when there is no infinitesimal changes of water volume during suction equilibrium stage. The diffused air volume measurement should be performed once or twice a day or more frequently when high pressures are used. The measured water volume changes should be adjusted in accordance with the diffused air volume.

TEST PROCEDURE

Multistage triaxial set up was carried out due to the limited specimens and the effect of the soil variability, which is often high in residual soils are also eliminated.

Multistage multi suction, shear test could assist in overcoming soil variability problem. In this case, the ϕ^b

value is determined with ϕ'. According to the unsaturated soil mechanics theory (D.G. Fredlund, H. Rahardjo, 1993), the ϕ' for different matric suction is the same for a particular soil sample. In this case, a multistage CIU triaxial test need to be conducted in order to obtain the ϕ' value. After the multistage test, another sample was set up to carry out the multi suction multistage test. The test procedures are as follows:-

i. The specimens are sampled and mounted in the modified triaxial setup with filter paper at the bottom of the sample. (This is to prevent the fine clay material from blocking the fine pores in the high air entry disc).

ii. Suction equilibrium and consolidation were carried out before the shearing process. Matric suction equilibration is generally attained in about one week or more.

iii. After consolidation to the required stress are maintained while the sample is sheared at a constant rate.

iv. At peak shear stress the axial force is immediately released until no significant shear resisting force, allowing the sample to recover elastically.

v. For the second stage of multi suction multistage shear test, the matric suction is increased to another higher suction value. Suction equilibrium has to be carried out first according to steps 2.

vi. The matric suction increases for every shearing stage.

vii. Since the ϕ' is the same for a difference suction value, the failure envelope can be obtained for a single peak value for every multi stage shearing. With the difference apparent cohesion, the ϕ^b value also can be found.

viii. This multi suction multi stage shear test can actually reduce the number of samples used and time in order to obtain the shear strength parameter of the unsaturated soil.

COMPUTER CONTROL

The triaxial test setup used for testing was fully computerized. This setup uses three Pressure Controllers for cell, back and lower chamber and a Digital Pressure Interface to measure and maintain pore water/air pressure respectively.

The computer can control the test itself according to specified conditions by using data fed back from test measuring devices, by processing it and transmitting to a pressure controller which make instant adjustments to the applied pressure by means of stepper motors. The Consolidated Drained (CD) triaxial strength tests with suction stabilization normally runs for days, this arrangement enables the test to be performed continuously with data collection left unattended.

Figure 8 GDS

TEST RESULTS AND DISCUSSIONS

Two sets of test results are presented here for discussions. The sample were collected at TP5 Level 1 (weathering grade IV) and Berm 4 (weathering grade III). Both the samples were collected from the massive sandstone area. A typical test results of :

1. Stress-strain curve for multi suction multistage.
2. Plot of continuous water volume change during suction consolidation.
3. Mohr circular plot for multistage CIU test results.

Are all shown in **Figure 8, 9 and 10** respectively.

From the CIU test results, friction angle ϕ' of 26^0 and 33^0 were obtained for sample at grade IV and grade III. Using the friction angle (ϕ'), parallel lines were plotted to obtain effective cohesion for various suction, shown in **Figure 11** and **Figure 12.**

The obtained effective cohesions are then plotted with matric suction to determine the value of ϕ^b (angle indicating the rate of increase in shear strength with respect to changes in $(u_a - u_w)$) in **Figure 13** and **Figure 14**. From the above plots the contribution of suction in shear strength (equation 2) gets no longer significant when the suction value gets higher. Shear strength of soils would be lower at higher suction value if compared to lower suction.

In addition to the above tests, soil-water characteristic curves were also studied for both laboratory and field tests. A typical plot of soil water characteristic curve at berm 4 (soil of grade IV) is shown in **Figure 15.**

The samples were collected at weathered sandstone location with weathering grade of III and IV, CIU test results of ϕ' =33 and ϕ' =26 justify the sample type and grade.

Much more samples will be tested in the future to verify these test results. In the final part of this research work, stability analysis of the slope will be conducted at various sectional profiles to determine the changes in factor of safety caused by suction.

CONCLUSION

The proposed multi-stage triaxial testing procedure to evaluate the rate of increment in shear strength ϕ^b concerning matric suction is possible provided that ϕ' is assumed to be constant at all suction level. Furthermore triaxial test on unsaturated soil specimens using multi-stage technique will greatly reduces the sample or soil variation and disturbances.

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