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Modified Shear Box Test Apparatus for Measuring Shear Strength of Unsaturated Residual Soil

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Abstract: Residual soils occur in most countries of the world but the greater areas and depths are normally found in tropical humid areas. Most of these soils exhibit high suctions for most of the year. The shear strength parameters, c' and ϕ', of soil can be obtained using conventional shear strength tests. However the conventional shear strength test equipments would not be able to measure ϕ^b value (change of shear strength to change in suction) without certain modification to them. This study describes the modifications that have been made to a standard shear box test apparatus to enable it to test soil samples in unsaturated conditions. The modifications include fabrication of an air pressure chamber, modifications of the shear box assembly inside the air pressure chamber, modification to the normal loading system, as well as additions of data acquisition devices to enhance the performance and simplify the usage of the modified shear box test apparatus.

Key words: Laboratory test, shear box, shear strength, unsaturated residual soil

INTRODUCTION

Residual soils occur in most countries of the world but the greater areas and depths are normally found in tropical humid areas. In these places, the residual soil (also known as tropical residual soils) forming processes is still very active and the weathering development is much faster than the erosion factor. The origin, formation and occurrence of tropical residual soils have been described in detail by Singh and Huat[1].

The deep groundwater condition is not unusual in tropical residual soils especially within steep slopes. Soils above the groundwater is certainly unsaturated, hence negative pore water pressure, which is also known as matric suction, plays an important role in controlling the shear strength and consequently the stability of many steep slopes.

Most residual soils exhibit high suctions for most of the year. The absence of positive pore water pressures except immediately after rain makes conventional soil mechanics for saturated soil irrelevant. In particular, the effective stress theories of saturated soil are not applicable at a practical level.

As the name suggests, unsaturated soil means soil that is not fully saturated, i.e. Soils which contain both air and water phases within its solid phase. However, in contrast with Bishop's[2] concept of unsaturated soil, it is not accepted that the state of stress in the water phase, rather than the degree of saturation, that should be used[3].

The two stress state variables most commonly used are the net normal stress, $(\sigma-u_a)$ and matric suction, $(u_a - u_w)$, which is found to be most satisfactory for engineering purposes[4]. This combination has the advantage of only one stress state variable is affected when the pore water pressure is changed. Or, in other words, the effects of change in total normal stress can be separated from the effects caused by a change in the pore water pressure. The shear strength equation has the following form:

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

Where:
- c' = Effective cohesion
- $(\sigma-u_a)$ = Net normal stress state of failure plane of failure
- ϕ' = Angle of internal friction associated with the net normal stress state variable $(\sigma-u_a)$
- (u_a-u_w) = Matric suction on the failure plane of failure
- ϕ^b = Angle indicating the rate of increase in shear strength relative to matric suction

The equation (1) describes a plane on a three-dimensional plot with the stress state variables $(\sigma-u_a)$ and (u_a-u_w) as the horizontal plane and shear strength as the ordinate. This 3D plot is also known as the extended Mohr Coulomb failure envelope. The equation assumes a planar failure envelope, the internal friction angle ϕ', remains essentially constant under saturated and

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unsaturated condition. At saturation, i.e. when matric suction goes to zero, the equation reverts to the shear strength equation for a saturated soil. Therefore this equation could be applied to both saturated and unsaturated soils depending upon the matric suction on the soil.

The parameter *c*' and ϕ' can be obtained using conventional shear strength tests. However conventional shear strength test equipment would not be able to measure ϕ^b value without certain modification to them.

The conventional triaxial test apparatus can be suitably modified to study the shear strength characteristics of unsaturated residual soil[5]. However this technique has a number of weaknesses. First of all, it is a very lengthy procedure. One multistage test series may take up to three months for completion. Secondly, the design of modified triaxial equipment is very complicated. Thirdly, the experimental setup of a triaxial test for unsaturated soil is very tedious. All the above reasoning makes the usage of triaxial testing very time consuming, cumbersome and not user friendly. Hence, an alternative method of finding the shear strength characteristics of an unsaturated soil, that is not so time consuming and complex in design, is needed to overcome the said weaknesses.

Shear box apparatus on the other hand is well known for its simple design and fast testing procedures. The direct shear box test is the oldest and simplest way of measuring the shear strength of a soil. It uses the principle of angle of friction test, in which one portion of the soil is made to slide along another by the action of steadily increasing horizontal displacement, while a constant load is applied normal to the plane of relative movement.

The standard test apparatus basically consists mainly of a rigid split box, with a top and bottom portion, placed in a shear box carriage. The carriage is seated on a pair of rollers that can move along a pair of grooved tracks; a motor connected to the shear apparatus controls its movement.

The specimen inside the shear box is sheared along the split plane by first applying a normal load via a load hanger, then moving the bottom portion of the box relative to the top portion. The top portion of the box is kept stationary by a horizontal force-measuring device. This measuring device, a proving ring and a dial gauge or more recently force transducers, measures the shear load resistance. In the normal shear box testing, as opposed the more versatile triaxial testing, drainage of the soil sample cannot be controlled. In such case, the soil sample is normally assumed or tested either as drained or undrained.

For the specific case of tropical residual soil, the soil is normally unsaturated. In order to investigate the shear strength characteristic of such soils, test apparatus such as the standard shear box has to be modified to simulate an unsaturated condition. Examples of earlier attempts to modify the shear box apparatus are described by Escaro and Saez[6] (6) and Gan and Fredlund[7].

This study describes a three phase modification that has been made to a standard shear box test apparatus to enable it to be used for testing soil sample in an unsaturated condition. A number of refinements have been made to the earlier designs of Escaro and Saez[6] and Gan and Fredlund[7]. These are described in the study.

MODIFIED SHEAR BOX TEST APPARATUS

The first phase of the modification involved fabrication of an air pressure chamber and modification to the normal loading system. The second phase was modifications to the shear box assembly inside the air pressure chamber. Whilst the third phase was addition of data acquisition devices to enhance the performance and simplify the usage of the modified shear box test apparatus to make it suitable for testing unsaturated residual soils.

Air pressure chamber and normal loading system: The first requirement of testing an unsaturated soil is the need to apply suction (u_a-u_w) to the soil sample. For this purpose, the modified pressure plate technique or axis translation technique[8], whereby both the pore-air, u_a and pore water, u_w pressures are raised into the positive range, making them controllable and measurable, is used. Thus, matric suction of much higher magnitude than the atmospheric pressure could be obtained without fear of cavitations.

To apply air pressure to a soil sample in a direct shear test, the shearing apparatus has to be enclosed inside an air chamber. This chamber must to be airtight and must be able to withstand very high pressure of at least 1000 kPa for the application of very high suction.

In this case, a stainless steel box measuring 300 mm by 200 mm by 200 mm high, with walls about 15 mm to 20 mm thick was constructed as the enclosure (air pressure chamber), as shown in Fig. 1. The air pressure chamber lid is 20mm thick and is clamped to the chamber wall using twelve 5 mm bolts. A 15 mm and a 5 mm diameter holes were drilled in approximately the middle of the lid to accommodate the normal load ram and the joint of the air pressure line respectively. The air pressure line is for the application of air pressure, u_a. Two more 15 mm diameter holes were drilled in the left and right sides of the air chamber wall to accommodate the rams in contact with the apparatus outside the chamber (load cell and motor driver unit). Another two 5 mm holes were drilled in the side of the chamber for water lines joints, i.e. for applying water pressure (u_w) to the soil sample.

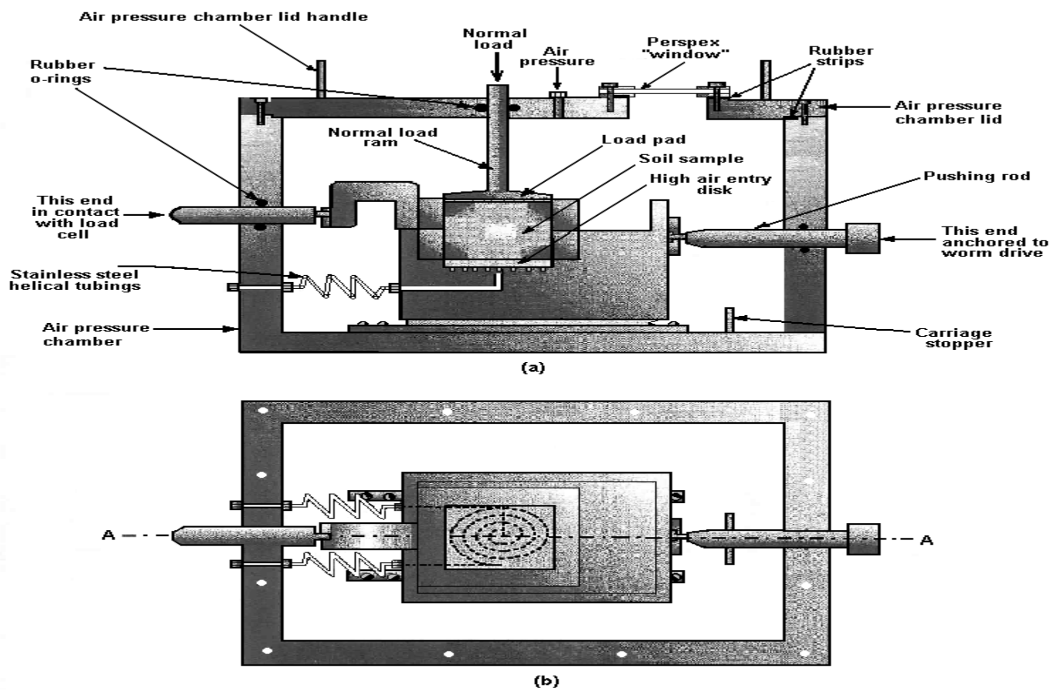

Fig. 1: Modified direct shear box assembly (a) section A-A (b) plan view

It is of interest to note that the air chamber lid was first fabricated solid and difficult to manage because of its weight. For this a Perspex window and a handle were fabricated to the lid. The window enables visual inspection of the insides of the chamber to be made; for example during the saturation of the high air entry disk (in case the water above the disk finishes), or before shearing commences (in case the clamping screws have not extracted). Apparently none of the earlier modified shear box design mentioned before has these features.

To ensure air tightness of the air pressure chamber, rubber strip was fitted at the periphery of the chamber lid and rubber o-rings were installed at all the above-mentioned drilled holes.

With the addition of the air pressure chamber to the test assembly, the original loading yoke and weight hanger used for the normal pressure had to be replaced to make allowance for the width and height of the air pressure chamber. In this case, a 200 mm long rounded tip stem was fixed to the loading yoke assembly to transfer normal load from the weight hanger to the soil sample inside the air pressure chamber (Fig. 1).

Shear box assembly: The second phase of the modification includes the modifications on the shear box assembly itself, the shear box carriage, an addition of sturdy helical stainless steel tubes as part of the water line and the motor driver unit to drive the shear box.

The two halves of the conventional shear box were replaced because the design of the original shear box did not allow for water-tightness of the bottom of the sample. A new solidly built shear box was fabricated complete with clamping screws. By applying silicon grease to the bottom half's outer walls, which just fit into the shear box carriage, water is ensured to flow only towards the high air entry disk.

It is of interest to note that in this design, the standard 60 mm x 60 mm size shear box was used, compared with smaller 50 mm x 50 mm size sample of the earlier modified design. Larger sample size is particularly important to tropical residual soil as the soils are usually non-homogeneous and antistrophic, making representative sampling particularly difficult[9].

Next the swan-neck yoke on the top half of the shear box was modified to allow for longer horizontal displacement, hence higher shear strain. This is because previous triaxial tests on unsaturated soils had yielded very high strains of more than 15%[5,10]. Figure 2 illustrates the modified shear box assembly.

The next important consideration after the air pressure applied was the pore-water pressure application. For this a water chamber or compartment was made in the form of spiral groove in the shear box carriage. A pair of funnels drilled into the carriage connects this water chamber to the water lines. On top of the spiral groove, a square 60 mm x 60 mm high air entry ceramic disk was fixed. This high air entry ceramic disk separates the air and water pressures, thus enabling independent control of pore water pressure (u_w) from pore air pressure (u_a).

Once the high air entry disk was saturated with water, air cannot pass through the disk by diffusion due to the ability of the contractile skin to resist the flow of air[3].

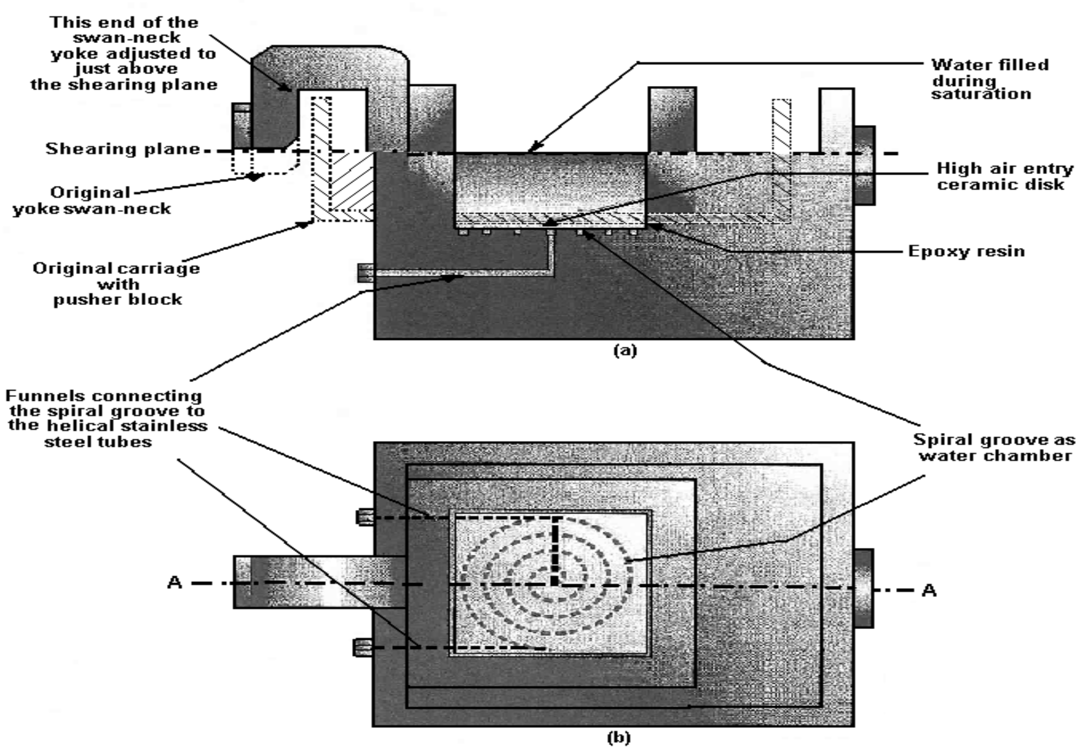

Fig. 2: Modified shear box in its carriage (a) section A-A (b) plan view

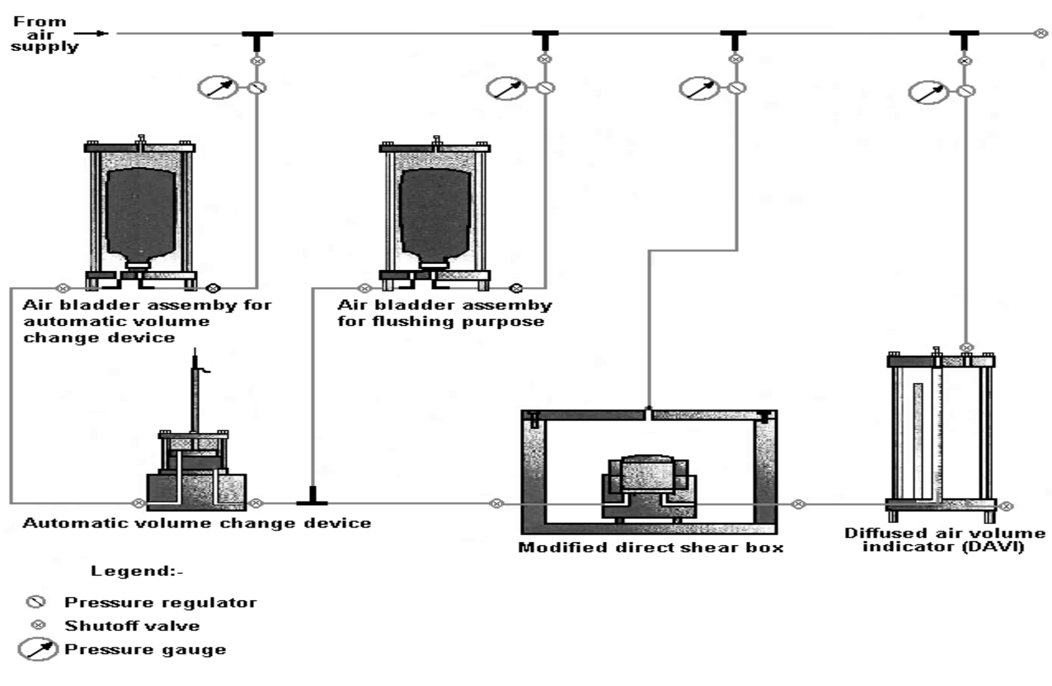

Fig. 3: Modified shear box test set-up for testing unsaturated residual soil

The spiral water grove chamber at the base of the current modified shear box carriage was designed to enable water to flow more swiftly and efficiently, especially during flushing, compared to the sharp corners found in parallel drains of the earlier modified shear box of Gan and Fredlund[7].

Data acquisition devices: The third and final phase of the modification involves the replacement of certain measuring devices that would simplify data collection and also additions to the experimental set-up to suit unsaturated soil testing procedures.

In a standard direct shear test, three sets of data are required and have acquired during the shearing process. They are the relative displacement of the two portions of the shear box (horizontal displacement), the vertical displacement of the sample and the shearing resistance applied to the soil sample.

To ease data collection and analysis, all data collection was computerized. Linear variable displacement transducers (LVDT) were used to measure both the vertical and horizontal displacements. Whilst a 10 kN capacity Wykeham Farrance load cell connected to the swan neck was used to measure the horizontal shearing forces.

In addition to the above three sets of data acquired using the said devices, for testing unsaturated soils, the vertical displacement of the specimen during consolidation and the volume change of water and diffused air during suction equilibrium are also required. These additional data are obtained before the shearing commences. During shearing, the volume change data are also required.

For consolidated drained tests, the water volume change has to be monitored to ensure no excess pore water pressure remains. In this case, the measurement of volume change was done by means of a Wykeham Ferrance automatic volume change device, which could measure the total volume change draining out of or drawn into the soil sample. This device was connected to the water chamber and water lines inside the air pressure chamber. The total volume change can be measured under a controlled back pressure by connecting the air pressure regulator to the device via an air bladder assembly, as illustrated in Fig. 3.

For shearing the soil sample, a displacement of rate 0.001 percent strain per minute was adopted, as has been established in the earlier work[5] as 'ideal' shearing speed for unsaturated tropical residual soil.

RESULTS AND DISCUSSION

A series of laboratory direct shear test with fixed suction was performed to see if the modified apparatus is suitable for testing the shear strength of unsaturated residual soils; to see if the results obtained comply with the extended Mohr Coulomb failure criterion of Fredlund *et al.*[4], as well as for comparison with the results of other similar studies on unsaturated tropical residual soils.

The soil samples used were obtained from a cut slope at KM 31 of the Kuala Lumpur-Karak Highway, near Kuala Lumpur, Malaysia. The soils are granitic residual soils of weathering grade VI, based on the commonly used classification of Little[11]. These soils had been formed over the commonly found porphyritic biotite granite bedrock of Peninsular Malaysia[12]. Table 1 summarizes the basic engineering properties of the soil samples.

Table 1: Basic engineering properties of soil sample

Liquid limit	95%
Plasticity index	50%
Specific gravity, G_s	2.68
Sand content	43%
Silt content	9%
Clay content	48%
Type of clay mineral: (X-Ray Diffraction)	Kaolinite

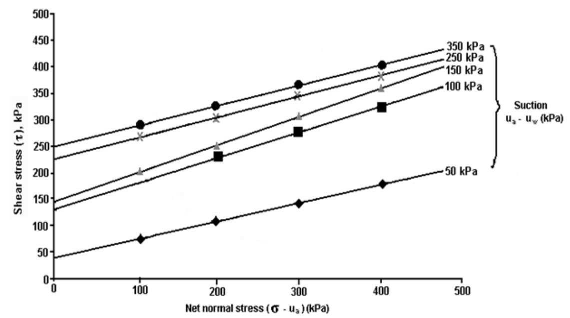

Fig. 4: Failure envelopes with respect to net normal stress, $(\sigma\text{-}u_a)$, for test with fixed suction

Tropical residual soils are usually non homogeneous and anisotropic, making representative sampling particularly difficult. In this study, block samples measuring 200 x 200 x 200 mm were collected from the site in metal boxes. These were then cut to the shear box size (60 mm x 60 mm) samples in the laboratory.

In running the test, the soil sample was first allowed to consolidate under a selected normal pressure. The normal stress, σ_n, was applied vertically to the specimen through the loading shaft. The net normal stress $(\sigma_n - u_a)$ was varied by varying the normal stress (σ_n) and the air pressure (u_a).

While the consolidation process brings the soil specimen to the desired $(\sigma\text{-}u_a)$ state of stress, the equilibrium process brings it to the desired $(u_a\text{-}u_w)$ or suction state of stress. The sample was then sheared at a rate of 0.001 percent per minute to ensure a drained condition.

Figure 4 shows plots of failure envelope with respect to net normal stress plane $(\sigma_n - ua)$ obtained from the direct shear test with fixed suction ranging from 50 kPa to 350 kPa. The soil effective angle of friction ϕ' is found to range from 20.3^o to 29.9^o, with an average ϕ' angle of 24.6^o.

Theoretically ϕ' should not vary too much[4]. In other words the lines for different values of suction, $(u_a\text{-}u_w)$, should be roughly parallel. However, Abdullah *et al.*[5], Escario and Saez [6], Gan and Fredlund [7], in their research found that the lines have a tendency to the slight divergence at increasing loads, which appears to be in agreement with this study.

Table 2: Values of ϕ' and ϕ^b of some tropical residual soils

Soil Type	ϕ'^{o}	$\phi^{b\ o}$	Test procedure	Reference
Granitic residual soil, grade VI	26	17	Unsaturated (CD) triaxial, multistage-single suction Saturated (CD) triaxial	Abdullah *et al*[5]
Granitic residual soil, grade VI	27	-	Saturated (CD) triaxial	Abdullah *et al*.[5]
Granitic residual soil	26.5	-		Hossain[14]
Sedimentary (Sandstone) residual soil				
- Grade V	26	26	Unsaturated (CD) triaxial, multistage	Mariappan *et al*.[15]
Grade IV	28	26	-multi suction	Mariappan *et al*[15]
Grade III	33	19		Mariappan *et al*.[15]

Table 3: Values of ϕ^b obtained by linearizing method

Net Normal Stress $(\sigma - u_a)$, kPa	$\phi^{b\ o}$
0	13.1
100	12.7
200	12.1
300	11.6
400	13.0

The average value of ϕ' obtained ($\phi' \approx 25^o$) is in a reasonable agreement with $\phi'$of similar tropical residual soils but tested using the modified triaxial test apparatus as summarized in Table 2. More examples of typical shear strength parameters of tropical residual soils can be found in Maail *et al*.[9] and Ting and Nithiaraj[13].

The apparent cohesion, c', conforms well to the theoretical concept of unsaturated soil, in that it clearly shows its increasing trend with increasing suction value. The *c'* intercepts increase from 40 kPa when the suction applied equals to 50 kPa, to 250 kPa at the suction value of 350 kPa (Fig. 4).

This certainly proves that soil suction does play a role towards increasing the shear strength of a soil and also verifies the unsaturated soil mechanics theory[3,4,16].

Figure 5 shows of failure envelope with respect to the matric suction $(u_a - u_w)$ plane. The non-linearity of the failure envelope of unsaturated soil as reported by earlier studies[5, 6,7] is evident in this plot.

If the method of linearizing the failure envelope suggested by Fredlund *et al*.[4] is to be observed, the distortion point or air entry value of the soil (ua-aw) ^{b} from the soil moisture (or water) characteristic curve of the soil would have to be found first.

Thus, by plotting the soil-moisture characteristic curve of a soil sample taken from the same test site and tested using the Rowe cell (which was suitably modified to employ the axis translation technique for application of suction), against the failure envelope with respect to suction (Fig. 5a), the failure envelopes could be linearized by utilizing the method suggested. Table 3 gives the resulting values from such exercise and ϕ^b being the angle of the second portion of the failure surface plot.

The value of ϕ^b is found to range from 11.6 to 13.1^o which an average value of 12^o. The ϕ^b value is lower than the ϕ' values, which is in agreement with the shear strength parameters of other similar tropical residual soil but tested using the triaxial test as shown in Table 2.

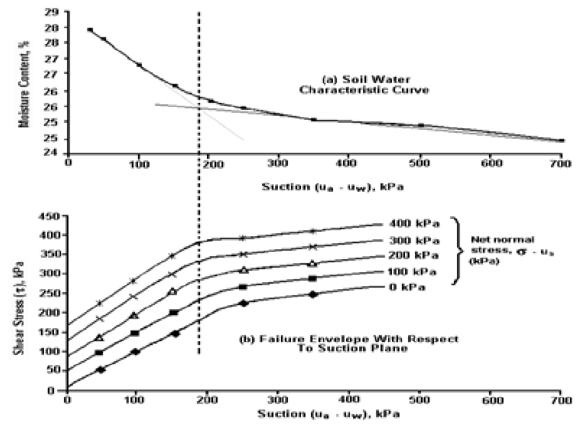

Fig. 5: Relationship between soil-water characteristic curve and shear strength

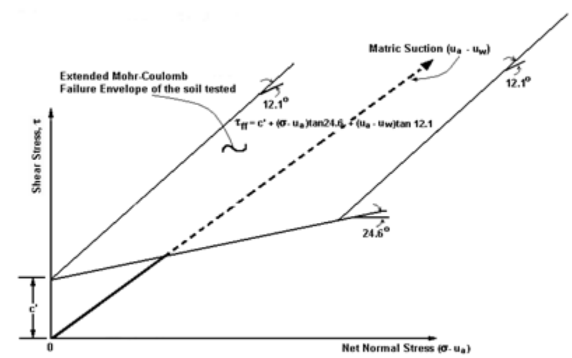

Fig. 6: Extended Mohr-Coulomb failure envelope of the soil tested

The three-dimensional Mohr-Coulomb failure surface plot for the residual soil tested is as shown in Fig. 6.

In terms of test duration, it is of interest to note that the direct shear test with fixed suction took on average only 11 days to complete, compared with the average of 75 days in case of shear strength test on similar residual soils using modified triaxial apparatus as reported by Abdullah *et al*.[5] and Mariappan *et al*.[15]. A major time saving could therefore be made using the modified shear box apparatus compared with the modified triaxial test apparatus, for determining the shear strength characteristics of unsaturated residual soil.

CONCLUSION

Conventional shear box test apparatus can be suitably modified to enable it to test residual soil sample in an unsaturated condition. The modifications that have been made include fabrication of an air pressure chamber, modifications to the shear box assembly inside the air pressure chamber, modification of the normal loading system, as well as additions of data acquisition devices to enhance the performance and simplify the usage of the modified shear box test apparatus.

From the test results obtained, the modified shear box test apparatus has been shown to be capable of producing acceptable and comparable results. The application of suction on the shear strength of the residual soil conforms the following: the higher the suction applied, the higher the shear strength becomes. The effect of suction can be quantified by the use of the extended Mohr-Coulomb failure surface plot. The values ϕ' and ϕ^b obtained are comparable to the modified triaxial test results done on similar tropical residual soils.

The modified shear box has a distinct advantage compared with the modified triaxial test whereby it allows a quicker hence cheaper shear strength test on unsaturated residual soil. The apparatus is also more adaptable and easy to handle due to its relatively simple design.

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