DESIGN DETAILS OF A MODIFIED RING SHEAR APPARATUS

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ABSTRACT
This paper presents design details of a modified ring shear test apparatus that can be used for the determination of the shear strength of unsaturated soils. Several advantages of the apparatus over the modified direct and triaxial shear test apparatus are discussed. The procedures to conduct different types of shear strength tests such as the constant volume tests, the consolidated drained tests and the constant water content tests over a suction range of 0 to 500 kPa using this apparatus are detailed. This apparatus also facilitates the simultaneous study of the soil-water characteristics during the shearing process taking into account of the stress history and shear deformations. In addition, the shear strength behavior of Barahona sand both under saturated and unsaturated conditions using the ring shear apparatus under constant volume (CV) conditions are also presented.

RÉSUMÉ
Cet article présente un appareil de cisaillement annulaire qui peut être utilisé pour déterminer la résistance des sols non saturés. Plusieurs avantages de cet appareil sur les appareils de cisaillement direct et triaxial sont abordés. L'appareil de cisaillement annulaire permet d'exécuter divers types d'essais de résistance en cisaillement tels que des essais à volume constant, des essais à charge constante ainsi que des essais à teneur en eau constante, le tout pour une gamme de suctions de 0 à 500 kPa. Cet appareil permet aussi de déterminer la courbe de rétention d'eau du sol en tout stade de cisaillement désiré en tenant compte des contraintes et des déformations imposées du au cisaillement. Des résultats d'essais saturés et non saturés sur du sable de Barahona dans de conditions de volume constant (VC) sont également pésentés.

1 INTRODUCTION

The conventional shear testing apparatus is modified through the use of a high air-entry disk in place of regular porous stone below the soil specimen in order to allow the application of a positive air pressure to control the matric suction while determining the shear strength of unsaturated soils using the axis translation technique (Hilf 1956). Such modifications are introduced in the direct shear, triaxial and unconfined compression test apparatus to determine the shear strength of unsaturated soils. Several investigators have used modified shear testing devices to determine the shear strength of unsaturated soils over the last several decades (Bishop & Donald 1961, Ho & Fredlund, 1980, Gan et al. 1988, Escario and Jucá 1989, Hettiaratchi et al. 1992, Ridley 1995, de Campos & Carrillo 1995, Vanapalli et al. 1996).

The modified direct shear tests are particularly convenient for the determination of shear strength of fine-grained soils using multistage tests (Fredlund and Rahardjo 1993). The thin specimens of approximately 20 to 25 mm that are used in the modified direct shear tests equilibrate under the applied matric suction in a relatively shorter period of time in comparison to thicker specimens in the triaxial shear tests. However, because of the smaller size specimens (typically 50 x 50 mm or 60 x 60 mm dimensions) used in modified direct shear apparatus, the shear strength behavior can be studied over a limited range of displacement.

The conventional ring shear device used for determining the shear strength of saturated soils has been modified to facilitate the determination of the shear strength of unsaturated soils. This paper presents design details of the modified ring shear test apparatus (Figure 1). This equipment consists of an automated data acquisition and control system to independently control the pore-air pressure and the net normal stress.

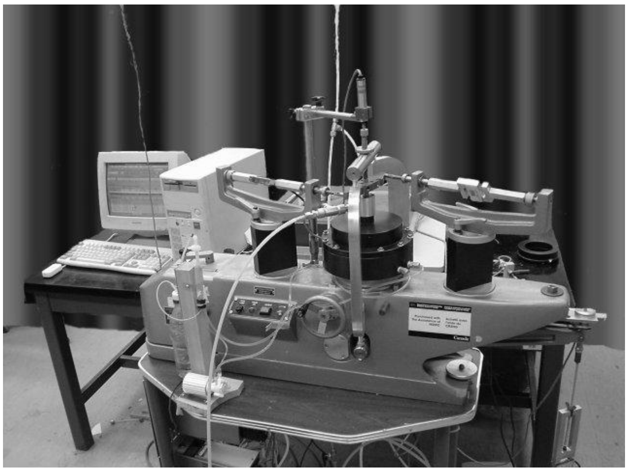

Figure 1 Modified ring shear apparatus for the determination of the shear strength of unsaturated soils.

The main advantage of the modified ring shear testing device over other devices such as the modified direct shear or triaxial shear test equipment lies in determining the shear strength behavior over an unlimited displacement of the specimen. This technique allows determining both the peak and residual shear strength behavior of unsaturated soils.

This is possible because the shearing deformations are circumferential, and as such the geometry of the shear surface is not affected by the shearing process. In addition, multistage stage testing can be conducted on the same specimen without any restriction of shear displacements. The design can also allow for measurement and/or control of the specimen volume, water content and suction. In other words, this apparatus indirectly facilitates the measurement of soil-water characteristics of the specimen in the ring shear device.

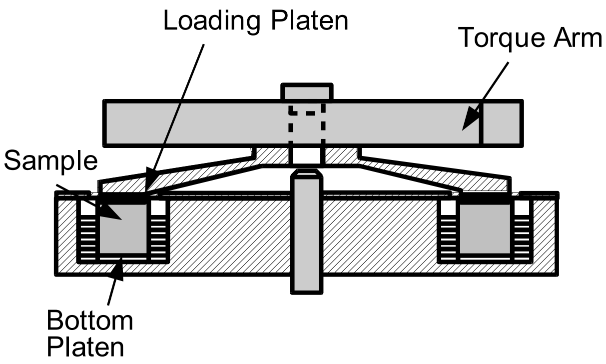

Figure 2 Schematic of original ring shear cell.

2 MODIFIED RING CELL

In most ring shear devices, the cell confining the specimen is composed of separate lower and upper halves (Bishop et al., 1971). During the shear test, the two halves are pushed apart leaving a tiny gap. The shearing plane will be along the gap between the halves of the cell. This is similar to the conventional direct shear box where one half of the box moves relative to the other during the shearing of the soil specimen. This method of testing is simple and provides a well defined shearing plane, but raises concerns as to nature and magnitude of the stress concentration at the boundaries of the specimen.

Garga & Infante Sedano (2002) presented a constant load/constant volume ring shear device to alleviate the stress concentrations (Figure 2). In this device, there is no mechanism used to induce the formation of a failure plane at a preferred location as in the conventional ring shear apparatus. Instead, the confining walls of the annular specimen are made of stacks of 2 mm thick rings. These rings can easily slide on each other so that they can independently move with soil at their respective depths. This method, essentially a ring simple shear test, can therefore be used without the generation of the stress concentrations typical of conventional direct shear tests.

Experimental studies have shown that at large strains, shearing was concentrated at a fixed height in the mass of the soil specimen. These observations were determined by analyzing the variation of fines content, within a uniform Unimin 2040 sand specimen, as particles were crushed during shear in constant load conditions (Figure 3). Figure 4 results support the above observation of displacement of the confining rings.

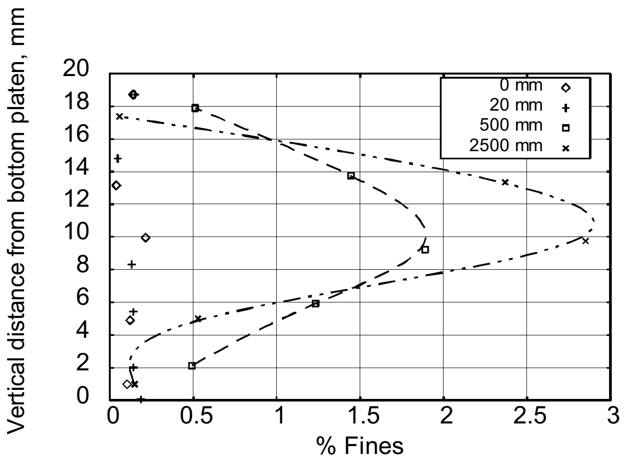

Figure 3 Observation of particle crushing within ring shear specimen at different shearing deformation. (Infante Sedano, 1998)

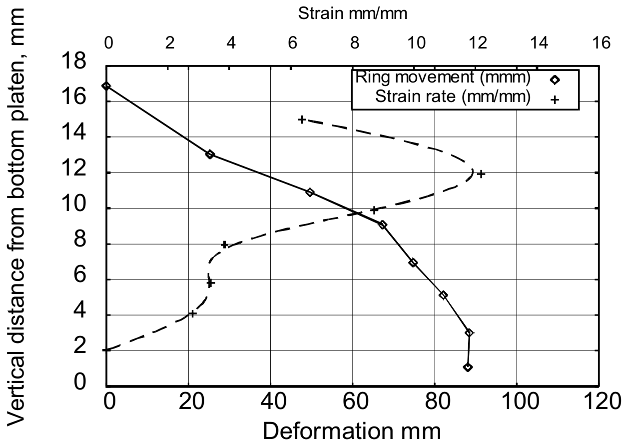

Figure 4 Shear strain within a ring shear specimen reflected in the relative displacement of the confining rings. (Garga and Infante Sedano, 2002)

The instrumentation on the device consists of a load cell connected to the loading arm of the ring shear device. The normal load acting on the specimen is increased by a factor of 10:1 due to the moment arm. The torque is measured using two independent load cells that resist the rotation of the top cap through the torque arm (Figure 2). The distance separating the point of application of the resisting forces measured by the two load cells is 152.4 mm (6”). The shear resistance of the specimen is calculated from the torque measured by these load cells. An LVDT is used to measure the vertical deformations. A computer controlled pressure regulator is used to adjust the pressure applied to a loading piston which transmits the force to the loading arm through the load cell. In this way, the normal load can be adjusted automatically by the computer.

Special provisions were made in this apparatus to determine the shear strength of unsaturated soils. For the purpose of the determination of the shear strength of an unsaturated soil specimen, the cell should be enclosed in a sealed chamber so that the specimen could be subjected to a high air pressure for the application of the axis translation technique. The chamber does not enclose the whole cell unlike the modified direct shear apparatus or other traditional ring shear devices. In addition, this particular cell is also not split at the mid height. Instead, a cap was used to seal a cell base similar to the details presented by Garga and Infante Sedano (2002) (Figure 5). The cap is screwed on the cell base with an O-ring to facilitate sealing. The instrumentation was also modified to include a pressure transducer in order to measure the applied pore air pressure. A servo controlled pressure regulator was also added to allow computer control of the applied air pressure to facilitate the computer to control both applied load and matric suction.

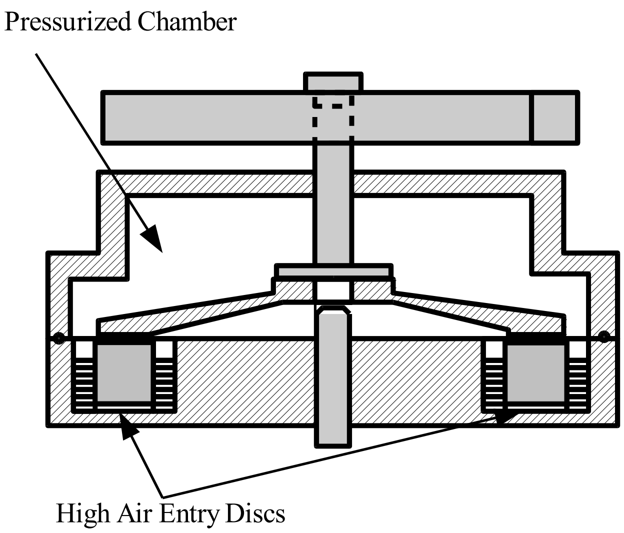

Figure 5 Schematic of modified ring shear cell.

The use of the cover to provide a pressurized environment for the specimen resulted in the need to use an extension for the torque arm. This extension was achieved in the form of a rod extending from the top platen through the cover that allows the torque to be transmitted from the specimen to the torque arm while a bushing maintains the seal.

Figure 6 Base of unsaturated ring shear cell with ceramic disks and inner confining ring stacks in place.

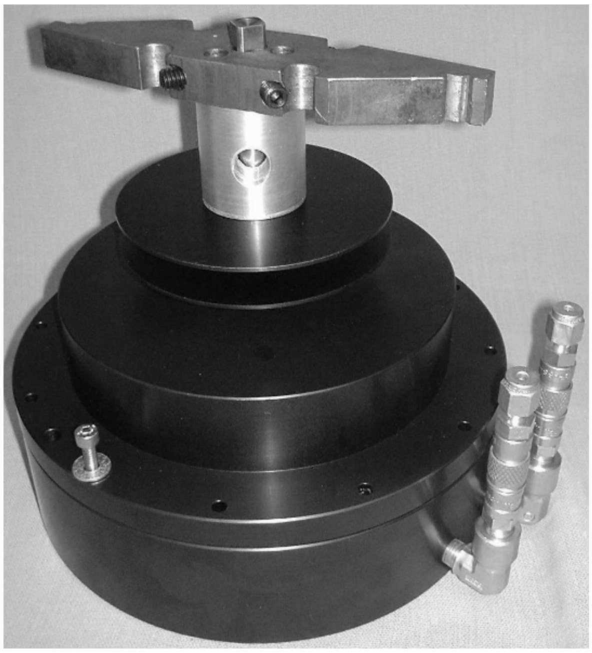

Figure 7 Assembly of modified ring shear apparatus

It was also necessary to modify the bottom platen. In its original form, this platen took the form of a corrugated brass ring. For the purpose of the testing of unsaturated soil specimens, it was necessary to replace this annular platen with another one equipped with a series of high air entry disks. The role of these high air entry ceramic disks is to act as a barrier to the air flow from the pressurized cell. They are also required to be pervious to water so that the water in the specimen can be in communication with the water in an external reservoir. In this way, a differential pressure can be established between the pore-air, u_a, and pore-water pressure, u_w. The difference between the pore-air and pore-water pressures is the matric suction, $(u_a - u_w)$.

In order to facilitate the movement of water to and from the specimen, it is preferable to maximize the contact area between the specimen and the high air entry ceramic. The ideal solution is a continuous annular ceramic ring. A continuous annular ceramic disk would not have been practical since ceramic disk is brittle and can rupture easily.

Another option is to place a solid ceramic disk on top of the confining ring. However, there will be practical difficulties associated with the use of solid ceramic disk because of its size (i.e., large diameter). The ceramic disk, in order to accommodate a flushing system below it would have to rest on a rigid base, similar to a Tempe cell. Because of the loads applied to the soil specimen are transferred to the disk, it would need to be placed perfectly flat over the whole area or risk inducing cracks in the ceramic due to bending moments. Such a system requires substantially more machining work than in the case of a ceramic disk that is conventionally used in Tempe cell and would complicate the handling.

As a practical alternative, a series of small circular ceramic disks encased in a brass ring was therefore chosen. The thickness of the ceramic disks is slightly smaller than that of the ring which causes depressions where the rings are and ensures good contact between the soil specimen and the ceramic disks. The edge of the upper part of the hole therefore serves as a roughening element in ensuring a good bond between the base platen and the soil specimen. A ceramic disk offers the advantage of a very compact shape that is easy to machine and is less likely to be damaged during handling. Furthermore, if one of the ceramic disks does get damaged or proves to be of inconsistent hydraulic properties, it is relatively simple and economical to replace it. The epoxy from Soilmoisture Corporation was used to provide both bonding to the brass ring and seal against the air pressure.

Two O-rings on the underside of the brass ring, and six additional small diameter O-rings around the screw locations, provide the seal so that the pressure of the water phase remains at atmospheric conditions despite the increase of the air pressure.

Because the water inside the specimen is in contact with air at pressures higher than atmospheric, there will be certain amount of dissolved air. The dissolved air can then move through the ceramic disk with the flow of water or through diffusion when the testing continues for a long period of time. It is therefore a standard practice to provide a mechanism by which the air bubbles that pass through the ceramic can be flushed out in order to maintain the continuity of the water phase when using the axis translation technique.

The need for flushing the underside of the ceramic disks requires that two openings be provided in the base of the cell. These openings are connected using a narrow channel that covers most of the area covered by the ceramic disks. A wave pattern was chosen instead the more common spiral groove that is conventionally used to accommodate the annular geometry of the ring shear cell. A pump is used to circulate the water through the channel. A pump draws water from the air trap and supplies it into the groove below the ceramic discs of the ring shear cell. The water and any air bubbles thus collected flow back to the air trap, thus completing the circuit (Figure 8). A capillary tube is also connected to the air trap. This tube can placed against a metre scale to visually determine the null point matric suction of the specimen. Alternatively, it can be connected to a volume gauge (Figure 9) for an automated suction measurement using the null point method, or to a weighing scale for water content control.

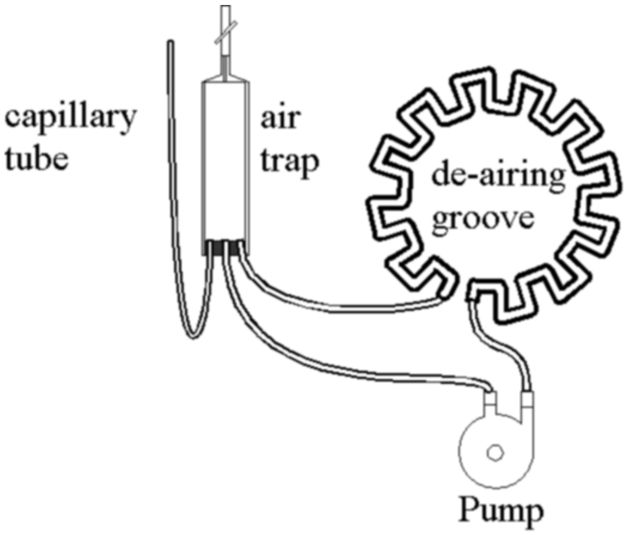

Figure 8 Idealized schematic of the de airing system, including the groove found below the ceramic discs, and the lines leading to the pump, and the air trap.

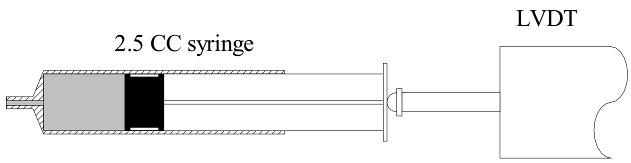

Figure 9 Schematic of a volume gauge for null point control of matric suction.

3 SPECIMEN PREPARATION

The soil specimens for testing under unsaturated conditions were prepared using static compaction technique. For this purpose, an annular aluminum piece matching the specimen dimensions is used to press the soil down in the annular cavity. The specimen is formed in multiple layers which are compressed with a fixed force.

The force is applied by a triaxial loading frame, on which a wide-footed braced aluminum bar is used to apply a centered vertical load on the specimen (Figure 10).

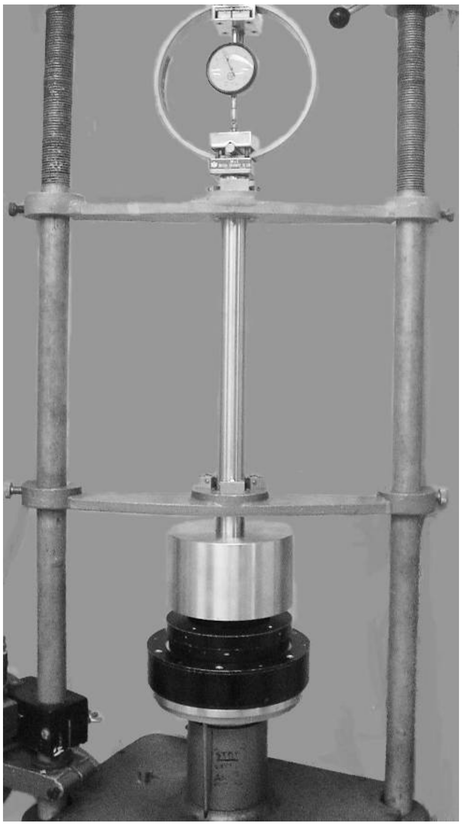

Figure 10 Static compaction loading frame.

An acrylic cell with the same internal dimensions as the ring shear test cell was also designed and constructed (Figure 11). This cell is used to verify the consistency of the specimen preparation method. The cell comprises a bottom platen that can be pushed up in precisely controlled increments so that slices of consistent thickness may be taken.

The acrylic cell is also equipped with side channels which allow the saturation. This technique can be used to saturate a compacted specimen once it has been formed.

The verification of the density of granular material in this device can be problematic since it is difficult to obtain a proper slice as the specimen has no cohesion. In order to conduct this test on such granular soils, it is necessary to give consistency to the specimen. A solution of water and gelatin can be injected into the specimen once it has been formed using the same channels present to permit the saturation of the compacted or dry specimens. This technique was earlier used to solidify crushed quartz sand (Garga & Infante Sedano, 2002).

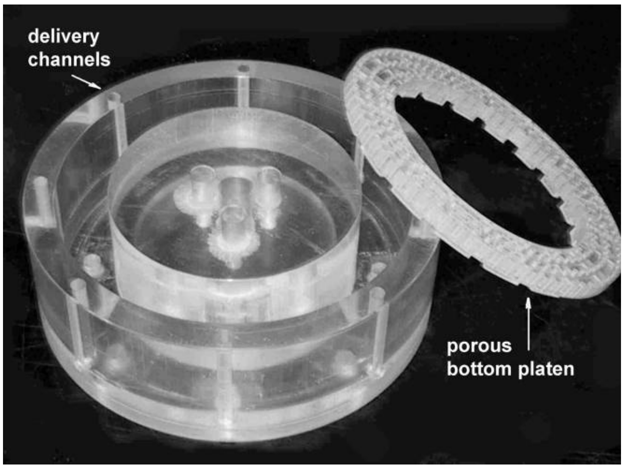

Figure 11 Density verification cell.

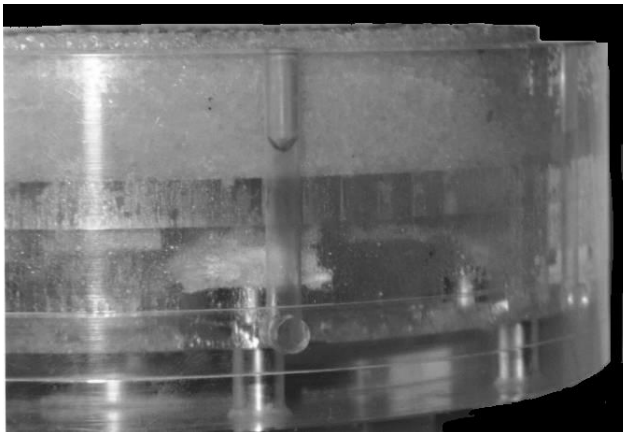

Figure 12 Specimen extrusion procedure

4 DIFFERENT TYPES SHEAR STRENGTH TESTS

The modified ring shear test device described above is equipped with electronic load cells for the measurement of the normal load and the resisting forces on the torque arm. LVDT's are provided to determine the vertical deformation of the specimen and displacement of the base platen rotation. Two servo motor activated air pressure regulators are provided to adjust the normal load and the specimen air pressure respectively through automated computer monitoring. In this system, as the water pressure is set to zero (i.e., atmospheric), the applied air pressure is equal to matric suction. Several different types of shear strength tests can be performed on the unsaturated soil specimens using the provisions included in the designed ring shear apparatus.

Figure 13 Extruder for specimen density testing.

4.1 Constant Load with Constant Water content (CLW) tests.

In this test, the applied normal stress remains constant during the test and since no drainage is provided, the water content remains constant throughout the test. There is no restriction on the drainage of the air phase. For the purpose of testing unsaturated soils, it is however required to measure the matric suction in the specimen during shear. Since the water content must be preserved, the null point technique is used rather than applying a constant pore air pressure.

In the null point test approach, any tendency of the water to leave or enter the specimen is countered by changing the applied air pressure such that the water content remains the same (Fredlund, 1973). A volume gauge must be used at the outlet of the flushing system to measure these volume change tendencies (Figure 2). The applied air pressure must be changed on a continuous basis to keep the specimen water constant. This technique is useful to determine the matric suction value in the specimen on a continuous basis. The initial, or compacted, matric suction of the specimen is also determined in this way before the shear test begins, and is used as the initial matric suction value.

The normal load applied on the specimen must also be modified so that the net normal stress remains unchanged. This is to accommodate the effect of unbalanced air pressure that acts as an upward force on the cross-sectional area of piston (which is in contact with the soil specimen) due to the applied air pressure. In other words, the applied load should be compensated to accommodate the influence of air pressure.

During this type of test, volume change of the specimen is monitored on a continuous basis. This information is useful to determine the density and void ratio of the specimen at any time during the test. Using this technique, the soil-water characteristics (i.e., the relationship between the water content and matric suction) can be established for all stages of testing during the shearing process.

4.2 Constant volume with constant water content (CVW) tests.

In this test, both the applied air pressure and normal load must be modified on a continuous basis so that neither the volume nor the water content of the specimen is allowed to change. In other words, the degree of saturation or the water content of the specimen in this test will be at a constant value throughout the test.

The continuous control of both the air pressure and the normal load requires the constant monitoring of the vertical deformation of the specimen to detect any tendency of the specimen to change volume. Again, the water content change is monitored through the use of a volume gauge and an LVDT to monitor the vertical deformations so that the volume may be measured and maintained at a constant value.

4.3 Constant load with constant suction (CLS) tests.

In this type of test, both the net normal stress and the matric suction (i.e., the applied air pressure) are maintained constant. Computer control is not necessarily required in this case since both pressure regulators can be set at a constant predetermined value. This test corresponds to the conventional consolidated drained (CD) tests.

The specimen will undergo volume changes which can be monitored on a continuous basis so that the density and void ratio of the specimen can be determined accurately at any stage of the test. The water content of the specimen can change during the shearing process in this test. It is therefore necessary to use a volume gauge to monitor the volume of water displaced to and from the specimen.

4.4 Constant volume with constant suction (CVS) tests.

In this test, the applied air pressure is maintained constant, but the normal load is modified on a continuous basis so that the volume of the specimen remains constant.

Because the matric suction is maintained constant, the volume of water entering or leaving the specimen must be continuously monitored to establish the relationship between matric suction and water content of the specimen. As the volume of the specimen remains constant, the degree of saturation will be a direct function of the water content.

The unsaturated shear strength behavior of Barahona sand determined under constant volume (CVS) conditions is presented in a later section.

4.5 Soil-Water Characteristic Curve (SWCC)

The ring shear test device can be used to determine the soil-water characteristic curve (SWCC). An unsaturated soil specimen in the ring shear apparatus can be saturated by applying a back pressure to the water phase. Once saturation of the specimen has been verified, the top platen and sealed cover are placed on top of the specimen. The matric suction is then increased at chosen intervals and the water content is allowed to reach equilibrium before the next increment of matric suction is applied. The amount of water leaving the specimen is carefully monitored at different values of matric suction at equilibrium conditions. An electronic scale can be connected to the computer such that the mass measurements of water leaving the specimen can be determined with a greater degree of accuracy using automation techniques during the test.

It is also possible to determine the SWCC while maintaining a normal load applied on the specimen to investigate the effect of the applied stress on the SWCC. Indeed, it is possible to establish the SWCC after shearing has occurred, or establish several SWCC at various stages of the shearing process simply by stopping the rotating table, saturating the specimen, and proceeding to increase the matric suction in increments. The ring shear device can be used an instrument to determine the soil-water characteristics during the shearing process.

5 SHEAR STRENGTH TEST RESULTS OF BARAHONA SAND FROM CVS TESTS

Shear strength tests were conducted on Barahona sand under saturated conditions in the constant volume ring shear test. The specific gravity, G_s of the Barahona sand is equal to 2.62 and its placement unit weight was 16.8 kN/m³. The saturated failure envelope is shown in Figure 14. The effective friction angle, ϕ' of the sand under saturated conditions is 26.1°.

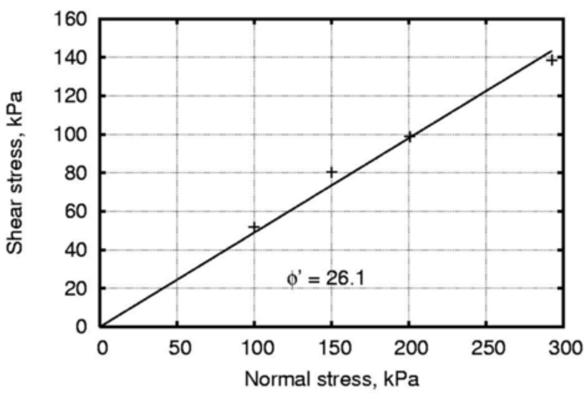

Figure 14 Failure envelope of Barahona sand.

The SWCC of the sand is shown in Figure 15. The sandy nature of the soil is illustrated by a low air entry value well below 10 kPa followed with rapid desaturation thereafter.

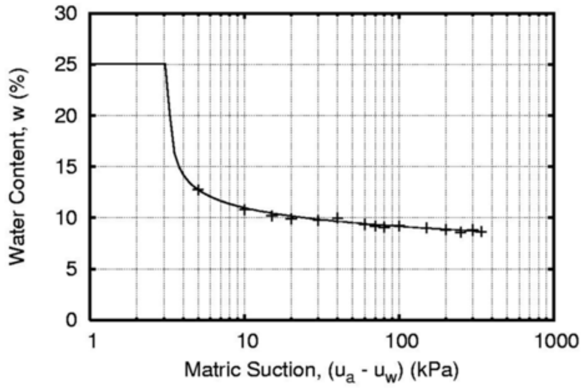

Figure 15 SWCC of Barahona sand obtained with a tempe cell using the axis translation technique.

Typical shear strength tests results using CVS procedure are shown in Figure 16. A multistage test was conducted on a sand sample under successive increments of the matric suction. The normal load was subjected to continuous variations to maintain constant volume of the specimen. A specimen in a loose state has a tendency to compress during shearing and hence the normal load is expected to follow a downward trend under such conditions. However, a dense soil has a tendency to dilate and would cause an increase in the normal stress. Once critical state/steady state has been reached, the normal load is expected to achieve a constant value.

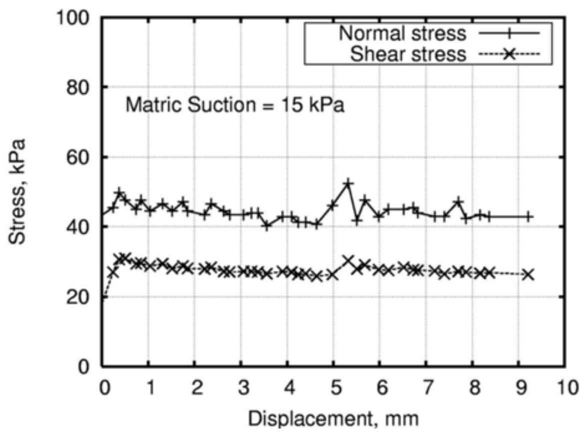

Figure 16 Typical constant volume shear test at a matric suction value of15 kPa.

In the case of cohesionless soils such as Barahona, where the effective cohesion is c' =0, the relationship between the shear stress, τ and the net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$ is given by:

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

where :

σ = the total normal stress
u_a = the pore air pressure
u_w = pore water pressure
ϕ' = internal effective friction angle
ϕ^b =internal friction angle with respect to matric suction

Since in a constant volume test the net normal stress changes in response to the tendency of volumetric changes of the specimen, this equation can be rewritten as:

$$\frac{\tau}{\sigma - u_a} = \tan\phi' + \frac{u_a - u_w}{\sigma - u_a}\cdot\tan\phi^b \quad 2$$

The relationship of the shear stress ratio $\tau/(\sigma - u_a)$ to the matric suction ratio $(u_a - u_w)/(\sigma - u_a)$ is shown in Figure 17. The data was plotted as stress ratios as the normal stress was not a constant value. The variation of shear stress ratio is non-linear with respect to matric suction ratio. The intercept on the y-axis is the *tan* ϕ' while *tan* ϕ^b is the slope of the curve. This behavior is consistent with the shear strength behavior of unsaturated soils.

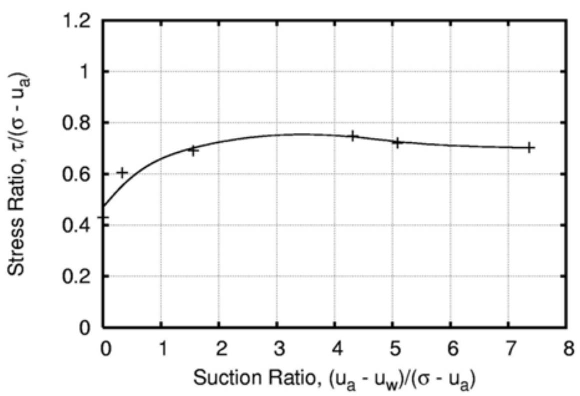

Figure 17 Stress ratio versus matric suction ratio for a CVS test on Barahona sand.

6 CONCLUDING REMARKS

A modified ring shear device is designed for the determination of the shear strength of unsaturated soils under different loading conditions. This device also offers the opportunity of studying the changes in the suction and water content relationship during the shearing process. In the present testing technique, the specimen geometry does not vary during the shearing stage. Due to this reason, the interpretation of the shear strength is simple and reliable. This equipment can be used to shear the specimen to much greater shear strains in comparison to conventional modified equipment such as triaxial and direct shear equipment used for measuring the shear strength of unsaturated soils.

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