DIRECT SHEAR BOX AND RING SHEAR TEST COMPARISON: WHY DOES INTERNAL ANGLE OF FRICTION VARY

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ABSTRACT

The direct shear box and the ring shear test as conventionally used for measuring the strength parameters of soil for use in classical stability analyses have the major disadvantage that the stress conditions in the specimen during the test are not known. The ring shear test was specially instrumented with 'artificial shear plane' to investigate the shear deformations and stresses acting on the sample. The 'artificial shear planes' were made from plane papers with ink-marks and introduced into the specimen. New data is presented from internal measurements in terms of photographs just before failure in the ring shear. An interpretation is given for the internal angle of friction and its relationship with the strain propagation in both the methods, and a comparison made. Results are presented from both the direct shear box and the ring shear test, and these are compared. Both the tests yield varying internal angle of friction when carried out on the same specimen and conditions.

Results reveal that the internal angle of friction obtained from a direct shear test is lower than that obtained from the ring shear test. It is established that the ring shear test has an inherent tendency to squeeze out material from the cell due to high stress accumulations at the outer edges. The inner edge is always understressed. The direct shear box has both of its sides equally stressed and this sharing of strains and stresses enable it to register lower bound values than those from the ring shear box.

The structures which appear in the direct shear box sample before and after failure indicate that the central portion of the specimen is in simple shear. A close examination of the failure mechanism in the direct shear box shows that kinking is the dominant mode of deformation, which is different from that in the ring shear. In the ring shear, the sample is very small, and there is non-equal distribution of stresses. When this non-equal distribution of stresses is accompanied by a tendency to squeeze out of material, kinking does not dominate.

KEYWORDS: direct shear box, the ring shear test, internal angle of friction

INTRODUCTION

To determine the relevant geotechnical parameters in a design situation, laboratory tests that simulate the in situ loading conditions as closely as possible should be performed (Kjellmann, 1951). The direct shear test and the ring shear test enable strength parameters to be computed. Other laboratory tests, which can be used, include triaxial and vane tests. These strength parameters are crucial in stability problem issues. Kjellmann (1951) reported the first direct shear devices. By that time it was reported that the strengths measured in the direct shear strength gave better agreement with those done in vane tests than those from ring shear or triaxial tests (Airey and Wood, 1987).

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At present, the reversal direct shear test is widely used to measure the drained residual strength of clays even though it has several limitations (Timothy and Hisham, 1994). The primary limitation is that the soil is sheared forward and then backward until a minimum shear resistance is measured. Each reversal of the shear box results in a horizontal displacement that is usually less than 0.5 cm. As a result, the specimen is not subjected to continuous shear deformation in one direction, and thus a full orientation of the clay particles parallel to the direction of shear may not be obtained (Skempton, 1985). This has a profound effect on the shear parameters obtained which many researchers including Skempton (1985) and Lupini *et al.* (1981) argued that this could not represent the true value of the soil strength in a practical sense.

The main advantage of the torsional ring shear apparatus is that it shears the specimen continuously in one direction for any magnitude of displacement. This allows clay particles to be oriented parallel to the direction of shear and a residual strength condition to develop. It has been reported that the ring shear test and other methods of soil strength measurements could yield varying internal angle of friction (Bishop, *et al.*, 1971).

This paper presents a description of the performance of the direct shear box and ring shear apparatus built for testing strength properties of soils. The objective is to evaluate the internal angle of friction (ϕ') from both the apparatuses and deduce whether variance is occurring. Further work shall aim at finding out why ϕ'could be varying by studying the strain distribution in the ring shear and the direct shear box. A comparison shall be made and a relationship between these stains and the angle of friction shall be analysed. For the study of stains, the use of coloured substances like ink-marks on paper which shall then be introduced to the respective apparatus to act as an artificial shear plane shall be utilised. This can aid the visualisation of strain propagation as shear continues.

1. BACKGROUND

The determination of shear strength parameters is of importance in geotechnical engineering. They are of direct application in slope stability evaluation, in the assessment of the engineering properties of soil deposits, which contain pre-existing shear surfaces, and in the assessment of the risk of progressive failure in stability problems (Bishop, 1971). The direct shear Box and the ring shear apparatus permit to assess these parameters. Other devices (laboratory vane, cone penetrometer, triaxial apparatus, plane strain and independent stress control 'triaxial' cells) are also used (Bromhead, 1992). Both direct shear tests on naturally occurring slip surfaces and ring shear tests have been shown to produce residual strength parameters comparable with the results of back analysis e.g. Bromhead and Dixon (1986). At failure (Morgenstern and Tchalenko, 1967), if stable yielding persists, the stress-strain curve is flat. However, for dilatant soils and for soils with clay content greater than 30%, unstable yielding occurs requiring a negative stress increment for a positive strain increment. Ultimately, stable yielding will be re-established at the residual strength where a dominant displacement discontinuity forms that is able to accommodate all further imposed deformation. These features are shown in Figure 1.

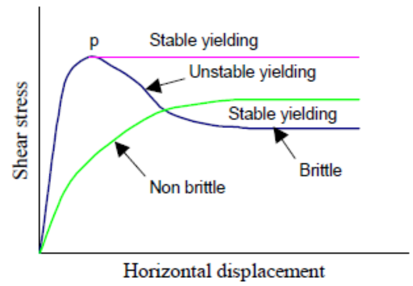

Figure 1. Typical stress-strain curve showing the stable and unstable yielding

Figure 1 explains peak and residual shear strength parameters. If shearing is continued after the peak point to the maximum displacement of the apparatus (indefinite for the ring shear), a curve of the type shown in Figure 1 for the brittle material is obtained (Manual of Soil Laboratory Testing, 1994). The shear strength reduces rapidly from the peak value at first, but eventually reaches a steady state (ultimate) value, which is maintained as the displacement increases.

2. THE DIRECT SHEAR BOX

The shear test is the simplest, the oldest and the most straightforward procedure for measuring the shear strength of soils in terms of total stresses. It is also the easiest to understand, but it has a number of shortcomings (Manual of Soil Laboratory Testing, 1994). A diagram of the apparatus and the shearing action is demonstrated in Figure 2.

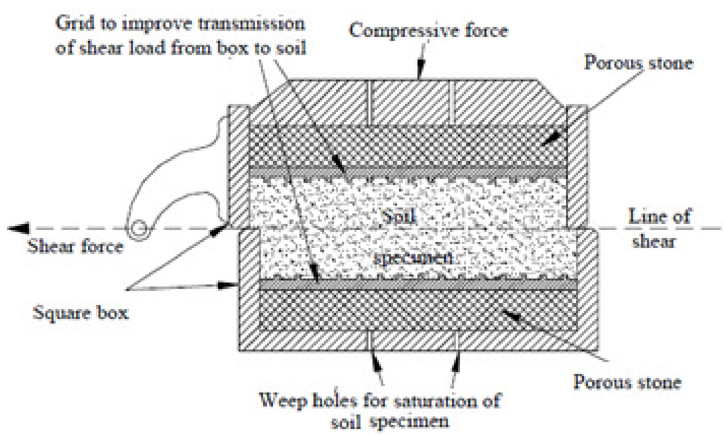

Figure 2. The shear box

The essential feature of the apparatus is a rectangular box, divided horizontally into two halves and containing a rectangular prism of soil. While the prism is subjected to a constant vertical compressive force, an increasing horizontal force is applied to the upper half of the box, thus causing the prism to swear along the dividing plane of the box. The test is normally carried on a number of identical specimens using different vertical stresses so that a graph of shearing resistance against vertical stress can be plotted. The vertical movement of the top surface of the specimen, which indicates changes in volume, is also measured and enables changes in density and voids ratio during shear to be evaluated.

3. THE RING SHEAR APPARATUS

The shortcomings raised up for the direct shear box may be overcome by using the ring shear apparatus (Figure 3) in which displacement is applied continuously in one direction. The ring shear specimen is annular with an inside diameter of 7 cm and an outside diameter of 10 cm. Drainage is provided by annular bronze porous stones secured to the bottom of the specimen container and to the loading platen. The specimen container confines the specimen radially, which is 0.5 cm deep (Stark *et al.*, 1994).

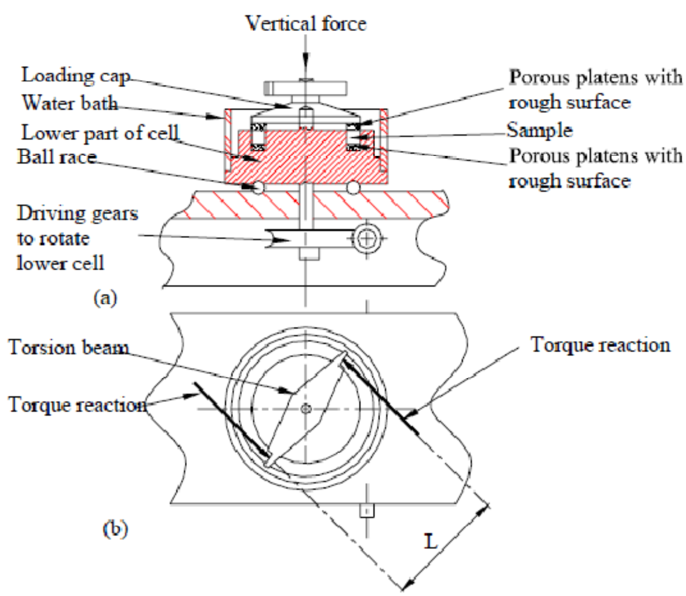

Figure 3. General arrangements of ring shear apparatus: (a) cross section, (b) plan showing torque reaction forces from load rings on torsion beam

An annular ring (Figure 4), subjected to a constant normal stress σ', is confined laterally, and ultimately caused to rapture on a plane of relative motion. The ring shear test is designed so that the total normal load and shear torque being transferred through the soil across the plane of relative rotary motion are accurately known, i.e. friction forces in the apparatus are demonstrably minimized or are measured where appropriate (Bishop *et al.*, 1971).

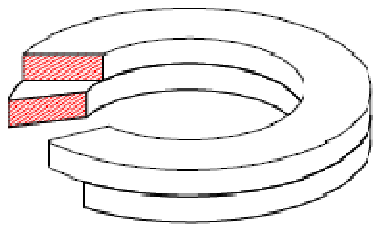

Figure 4. The Ring Specimen showing the shear plane

4. TEST PROCEDURE AND PERFORMANCE

4.1. DIRECT SHEAR TEST

The test procedure was started by carefully choosing test samples satisfying BS 1377: Part 7: 1990. The specimen preparation procedure was adopted from that used by Mesri and Cepeda-Diaz (1986) and BS 1377: Part 7: 1990.

Specimens were carefully brought to laboratory for testing. Loss or gain of moisture by the sample was avoided at all stages of preparation by keeping the sample in plastic bags and also carrying out operations in humidified atmosphere. Three similar specimens were prepared from a remoulded cohesive sample, for testing under three different normal pressures: 100 kPa, 200 kPa and 300 kPa.

The cross sectional area of the shear box was measured and recorded. The thickness of the sample was determined and its volume calculated. The volume of soil to be tested was calculated in advance. The mass required to produce the desired density was weighed out and its moisture content recorded. Finally, this soil sample was rammed into the shear box in three layers and an effort was made to utilize the whole of the material which would result in a soil density as it was in its original state. The pressure block was now placed over the sample thus rammed in, the shear box was set on the table of the loading equipment, and the loading yoke was fitted in. The weight of the pressure block and of the loading yoke represented part of the normal load, and was recorded.

A mass corresponding to the first normal load was placed on the lever, and the computer-operated shear box was then set to begin recording results, the sample being submerged in the water bath. Three shear boxes with loads 100 kN, 200 kN and 300 kN were set to begin recording almost simultaneously, and the results obtained after about 4 days.

4.2. THE RING SHEAR

Because comparison of the two apparatuses was the objective of this project, the same soil sample was used with same normal loads. The same rate of displacement as used in the shear box was applied although (Manual of Soil Laboratory Testing, 1994) the rate of displacement was not critical because the fully drained condition was bound to be reached eventually. By using the same rate of displacement for both apparatuses, comparison was justifiable, and differences then likely to occur could be argued upon. The test specimen was an annulus of 5 mm thickness with an outer diameter of 100 mm and an inner diameter of 70 mm.

The remoulded specimen used in this apparatus was confined radially between concentric rings, and vertically between porous annular discs with relatively rough surfaces. Vertical predetermined pressure was applied to the specimen through the upper porous annulus by means of a lever-arm arrangement counter-balanced using hanger weights. The cell which contains the specimen and removable was sub-merged in a water bath during the test. A motorised drive unit rotated the lower part of the cell while a matched pair of calibrated load rings, which enable the restraining torque to be determined, restrained the upper part. The results are presented in Appendix 4.

4.3. TEST ON STRAINS AND STRESSES IN THE SOIL SAMPLE

4.3.1. TEST 1

To simplify the visualisation of strains in a sample under shear, an artificial shear plane was desirable. The design of this plane was simple. Normal plane paper was chosen because it could absorb dye which when introduced inside the soil sample to form the artificial shear plane could suggest how the strains propagate under applied load. The thin section of the paper could also not interfere with the material's reaction during shear. It was desirable to make the paper smaller in the cavity to enhance more of sand-to-sand contacts. This is shown in Figure 5.

Figure 5. Annulus paper ring being fitted into the cell cavity

As normally shear planes in the ring form closer to the upper platen (Bromhead, 1994), it was necessary to introduce the paper as near to the upper platen as possible, and care was exercised to make the paper uniformly horizontal. This was achieved by firstly pouring the dry sand in the cavity of the ring shear apparatus to about 3 mm depth then by using the top platen, applying a slight pressure into the sample and slightly rotating the platen to obtain a near horizontal surface. This formed the surface of the artificial shear plane where the paper laid.

At this stage, ink-marks were made at the centre of the paper and at edges, after which sand was filled in the cavity to cover the paper completely and levelled off. As this test was not intended to find the strength of the material but rather the propagation of the strains, it was not submerged in the water bath. The only reason was to avoid water saturating the sample thus spoiling the paper. Figure 6 shows the ink-marks spread at strategic points over the annulus paper.

Figure 6. Ink-marks spread strategically and ready for the test

The cell was placed on the frame of the test apparatus. Grease was applied to the cell centring spindle and the upper platen placed in position on top of the specimen. The water bath was not filled with water for reasons as described above. The counterbalanced loading yoke was then placed in position on the upper platen and just enough downward force was applied to ensure that the yoke was properly seated.

There was no need to mount the vertical deformation gauge or transducer since strength parameters was not the objective of this test. Thus the consolidation stage was bypassed.

4.3.2. SHEARING

A rate of angular displacement was set to 0.048 degrees per minute (Manual of soil laboratory testing, 1994). There was no forming of the shear plane as stipulated in the BS 1377: Part 7: 1990 and in theory since the paperwork was a mere artificial shear plane as it formed a discontinuity in the specimen already. The drive unit was set, with a change wheel order of 45-45 and gear lever position that enabled speed of 0.048 degrees per minute to be obtained. Shearing was stopped when the adjustable degree scale etched from 0-90°, which was enough to visualize the strain propagation. If shearing was allowed to continue until residual strength was achieved, then the strains registering on the paper could have overwritten each other.

4.3.3. TEST 2

Instead of an artificial shear plane, the cavity was filled with only sand, with spots of carefully coloured sand with ink made. Laboratory BS test sieve 63 µm was used to sieve sand sample supplied from the laboratory store to produce a clean size fraction with this desirable characteristics. A small portion of dry sand about 30g was mixed with ink to form 'black sand'.

In most published work the conditions of this sample preparation are not described, but since the objective of the experiment was to give an indication of strain propagation, this was not a problem. Besides, this could easily be assimilated into published procedures. This mixture was then presumed to be ready for demarcating the edges of the cavity where strains are assumed to be having the highest effect.

The other portion of the sand passing BS test sieve 63 µm was placed in the cavity at a reasonably high density by slow pouring at high velocity, i.e. from a relatively high drop (Manual of soil laboratory testing, 1994). A drop of about 450 mm was enough. The sand was filled up to 2/3rd of the cavity, and as Test 1, the 'black sand' carefully introduced to the ink marks centre and sides of the annulus ring. Topping up of the cavity was then achieved using the other portion of the sand. Figure 7 shows the 'black sand' already in place.

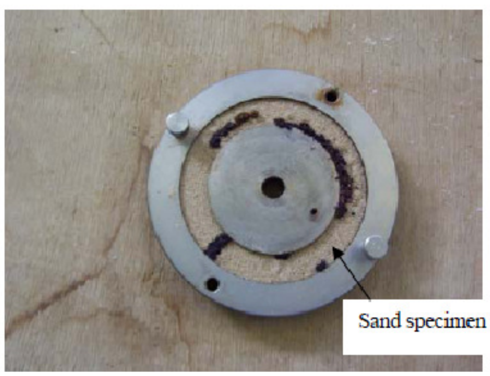

Figure 7. 'Black sand' spot in a ring shear

The procedure for shearing was as that described in Test 1.

5. RESULTS, ANALYSIS AND DISCUSSION

5.1. THE RING SHEAR TEST

5.1.1. TEST ON SHEAR STRAINS

Two types of tests were carried out. The first type was non-strength testing. The second one was strength testing where the internal angle of friction was obtained and a comparison made with that obtained from the one from the direct shear box. Figure 8 shows the artificial shear plane after the experiment. Figure 9 shows the 'black sand' after the experiment.

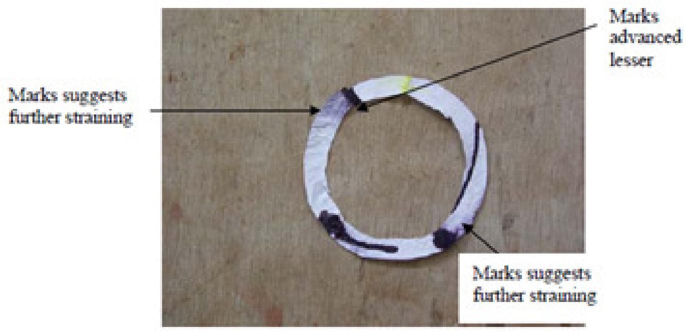

Figure 8. Ink-marks after the test

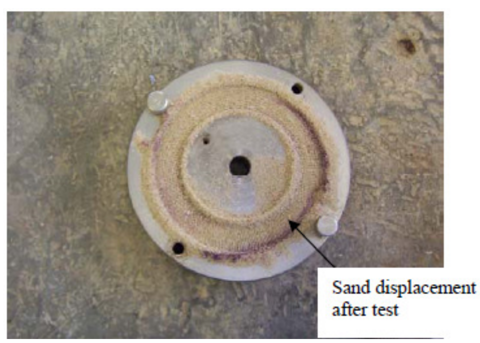

Figure 9. 'Black sand' marks after the test

It could be seen that there are more black spots on the outer edges than on the inner edges that implies that strain distribution is non-equal. Furthermore there is a tendency of material to squeeze out of the cell. This is observed in the Figure 10.

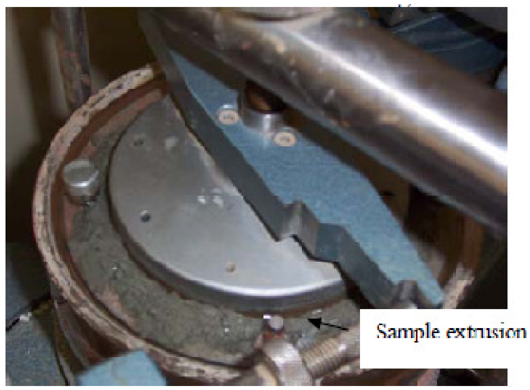

Figure 10. Extrusion of material due to high strains and stresses on the outer edges during shear

The earliest observed manifestation of strain is rotation or a movement of the particle orientation in the direction of shear with respect to the original position in the sense of the relative displacement of the two halves of the annulus ring. As the manifestation of strain is more on the outer edges than on the outer edges, stress increases, and material is extruded out or there is tendency of extrusion. If the upper platen is installed in such a manner that no gap is left for extrusion, then stress distribution is non-equal as ‘piling up’ of the stresses is the resultant, and can explain why the internal shear strength may be different than that obtained from other ordinary apparatuses.

The squeezing out of material implies that the sides of the ring are stressed more than the inside, which does not in practical sense happen in the direct shear box. The following schematic diagram (Figure 11) is a reproduction of diagrams Figure 8, 9 and 10 and shows from a geometrical consideration that the strains are varying across the sample.

Figure 10 showed that there is a marked tendency of material to squeeze out of the cell during test. This is an inherent property of the ring shear. The squeezing out of material results in stress concentration on the edges of the ring, and although this factor could be small, it can explain why the ring shear result differs from that of the direct shear box, which has a different mechanism in operation and failure of material, and will be seen later.

The observations of the movement of the strains have been shown, and it can be further argued that the spread of the ink suggests that at the shear plane, soil is dynamic. It does not stay in one place thus there is no smooth-shearing. This will continue in the direction of shear until the test is stopped. Sliding shear behaviour, in which the proportion of platy, low-friction particles is sufficiently high for a well-formed, polished sliding surface of strongly oriented clay to develop, is well established in the literature (Lupini, Skinner and Vaughan, 1981). The test on the ‘black sand’ being introduced into the shear plane tends to produce results that agree with the sliding shear behaviour.

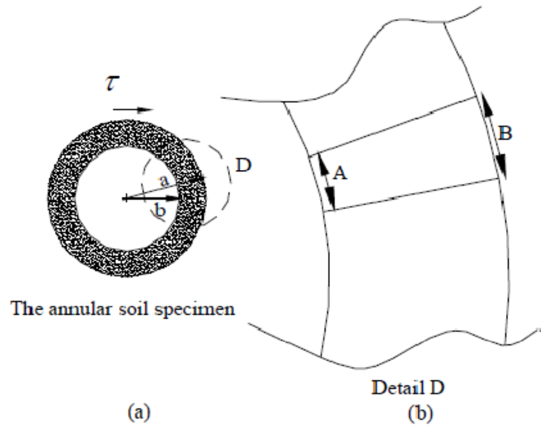

Figure 11. Strain distribution across the sample in an annulus ring which shows that theoretically strain A is less than strain B

Differential strain distribution across the sample, which results in non-equal stress distribution, has been established so far. They cause non-homogenous distribution of strength in the ring. The development of strain given by letter S1, S2 and S3 (Figure 12) may be followed in detail. The first indication of its formation is when testing has been started. As motion proceeds, the strain tend to follow Newton's first law of motion, which states that object in motion tends to stay in motion with the same speed and in the same direction. The onset of their development is already apparent in Figure 8 where the test was stopped prior to failure to study the strain propagation behaviour.

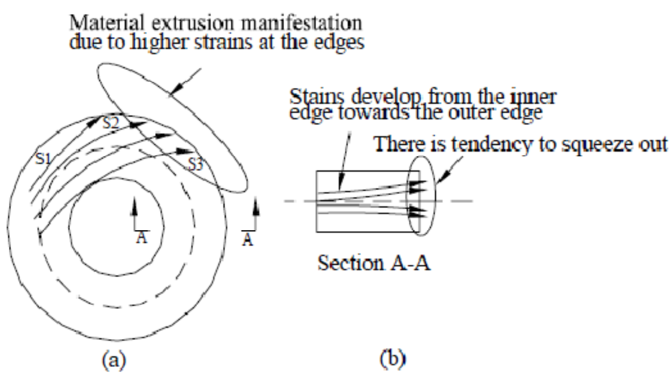

Figure 12. Material extrusion is almost inherent in a ring shear as strain propagation shows that the strains eventually 'pile up' at the edges

Subsequent motion factors the strain even further, and they start to pile up at the edges, in a way to say that the particles are looking for a way out, which is not allowed by the upper platen and also by the downward force being applied. As already established, if the upper platen fails to cover the sample completely and leaves gaps, extrusion begins, and the whole experiment fails before substantial results could be obtained. Returning to the gross material, it is clear that the inner edges, which are practically understrained, do not suffer from material extrusion.

5.1.2. TEST ON SHEAR STRENGTH

The test involved change in the normal effective stress (100, 200 and 300 kPa) to define the failure envelope obtained from the ring shear apparatus. The results are summarised in the Figure 13 (a) and (b).

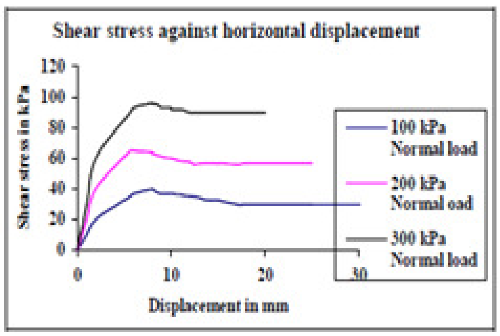

Figure 13(a). Shear stress against displacement

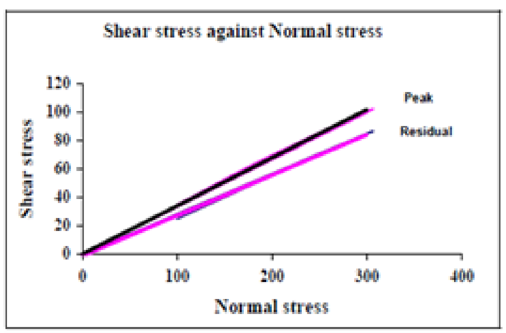

Figure 13(b). Shear stress against Normal stress

The internal angle of friction for peak and residual are 18.7° and 15.9° respectively.

5.2. THE DIRECT SHEAR BOX

5.2.1. TEST ON SHEAR STRAINS

Figure 14 shows a section taken from specimens that were sheared to residual values. A schematic interpretation was reproduced and is shown in Figure 15.

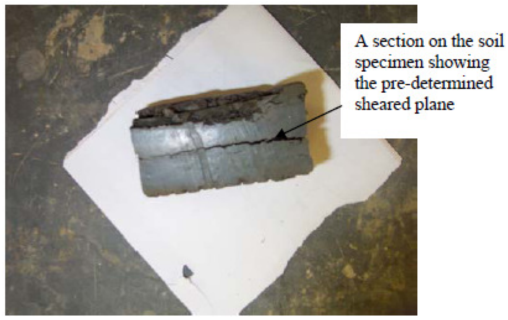

Figure 14. A section on a sheared specimen

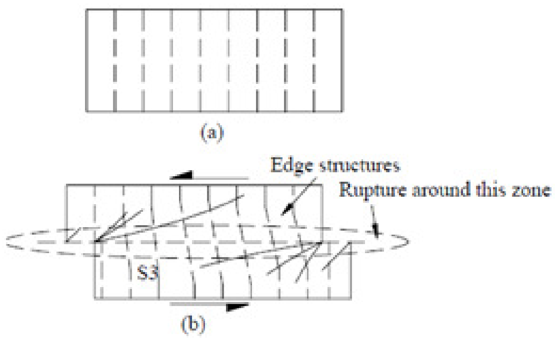

Figure 15. Schematic drawing of the strains before and after the test

Figure 15(a) shows the unstrained state. Figure 15(b) shows the earliest observed manifestation of shear strain, which is a rotation of the average particle orientation with respect to the original S3 direction in the sense of the relative displacement of the two halves of the box. This originated from the edges and extends towards the centre. As the displacement increased the strains multiplied in a discrete sequence and at diminishing positive angles to the horizontal. Ultimately, a continuous zone separating the top from the bottom of the box marks the end of shearing as failure is reached. It is then noted here that both the loading sides of the box cause high stress concentrations and local straining is intense unlike the ring shear where stress concentration is only on the outer edges.

However, some unexpected scenario developed in the direct shear box. The perforated grid plate has tongs, which dig into the sample and cause stress concentrations around them as shown in Figure 16.

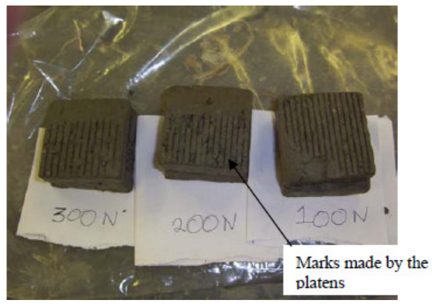

Figure 16. Platens dig deeply into the sample

Figure 17 is the schematic diagram reproducing the scenario in Figure 16 and explains in a theoretical background why the strains and stresses are higher at the platens. This differs from the ring shear whose porous disc does not have tongs that dig into the sample. The ring shear top cap has platens too, but they do not dig deeply into the sample and so have no much influence on the strength values of the specimen under test. This is shown in Figure 18.

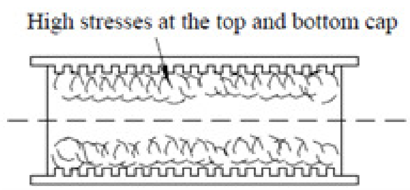

Figure 17. Schematic diagram showing the influence of the tongs on the specimen

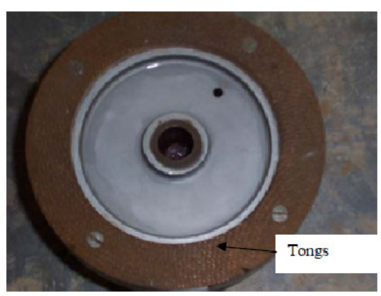

Figure 18. Upper platen of the ring shear detailing the tongs

5.2.2. TEST ON SHEAR STRENGTH

The test involved change in the normal effective stress (100, 200 and 300 kPa) to define the failure envelope obtained from the shear box and are presented in Figures 19, 20 and 21.

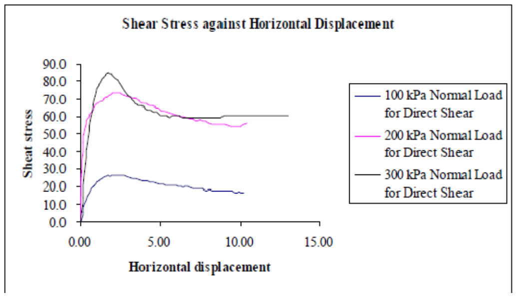

Figure 19. Result of shear stress versus horizontal displacement

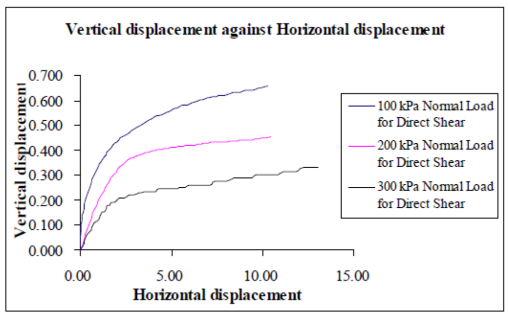

Figure 20. Graph of vertical displacement against horizontal displacement

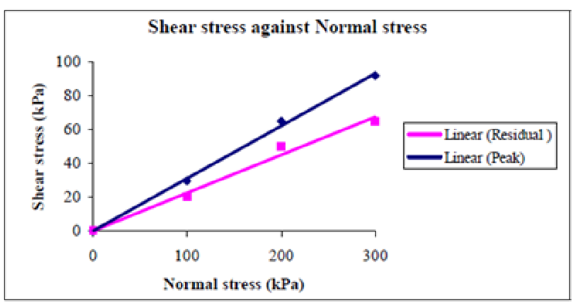

Figure 21. Failure envelope for direct shear test

The internal angle of friction for peak and residual strength are respectively 17.3° and 12.6°.

CONCLUSIONS

The internal angle of friction obtained from the direct shear box was lower than that obtained from the ring shear test. The ring shear test has an inherent tendency to squeeze out material from the cell due to high stress accumulations at the outer edges. The inner edge is always understressed. The direct shear box has both of its sides equally stressed and this sharing of strains and stresses enable it to register lower bound values than those from the ring shear box.

The perforated grid plate that is used to hold tight the sample during testing in the direct shear test caused unexpected stress concentration around them. The stresses mobilized at the predetermined shear plane are thus lower by a small fraction, and lead to the development of lower bound values of strength parameters obtained.

The structures which appear in the direct shear box sample before and after failure indicate that the central portion of the specimen was in simple shear. This confirms the interpretation of the shear box suggested by Hill (1950). A close examination of the failure mechanism in the direct shear box shows that kinking was the dominant mode of deformation, which was different from that in the ring shear. In the ring shear, the sample was very small, and there was non-equal distribution of stresses. When this non-equal distribution of stresses was accompanied by a tendency to squeeze out of material, kinking did not dominate. It is concluded that kinking only dominated if the sample was of reasonable size, which was the case in the direct shear box.

FURTHER WORK

Further studies are necessary to enable a detailed explanation as to why the results from the direct shear box and the ring shear test differ. In respect to that, the following are the key areas that need further work.

1. A method for optical observations should be incorporated to study the microscopic structures subjected to shear. A polarizing microscope as that used by Morgenstern and Tchalenko (1967) could enable a clear understanding of the kinking theory.

2. In the analysis of the direct shear box and the ring shear test, the top cap is allowed to move vertically but is prevented from rotating. A study to find out the effect of its rotation is necessary. This is because in most real direct shear box devices (Potts *et al.*, 1987), the top cap has some freedom to rotate and can thus influence the results obtained.

3. It has been established that there are differences in the results obtained from the direct shear box and that from the ring shear box. A study is necessary to establish which one yields the true strength values.

REFERENCES

1. Airey, D. W., Wood, D. M. An evaluation of direct simple shear tests on clay; Géotechnique; Vol. 37, No. 1, 1987, pp. 25-35.
2. Bishop, A. W. The influence of progressive failure on the method of stability analysis; Géotechnique; Vol. 21, No. 2, 1971, pp. 309-319.
3. Bishop, A. W., Green, G. E., Garga, V. K., Anderson, A., Brown, J. D. A new ring shear apparatus and its application to the measurement of residual strength; Géotechnique; Vol. 21, No. 4, 1971, pp. 273-328.
4. Bromhead, E. N. The stability of slopes; Blackie Academic & Professional, Glasgow, UK, 1992.
5. Bromhead, E. N., Dixon, N. The field residual strength of London Clay and its correlation with laboratory measurements, especially ring shear tests; Géotechnique; Vol. 36, No. 3, 1986, pp. 449-452.
6. Hill, R. The mathematical theory of plasticity; Oxford: Clarendon Press, 1950.
7. Kjellmann, W. Testing the shear strength of clay in Sweden; Géotechnique; Vol. 2, No. 3, 1951, pp. 225-235.
8. Lupini, J. F., Skinner, A. E., Vaughan, P. R. Drained residual strength of cohesive soils; Géotechnique; *Vol. 31, No. 2,* 1981, pp. 181-213.
9. Manual of Soil Laboratory Testing. Permeability, Shear Strength and Compressibility Tests; John Wiley & Sons, Inc., New York, 1994.
10. Mesri, G., Cepeda-Diaz, A. F. Residual shear strength of clays and shales, Géotechnique; 36(2), 1986, pp. 269-274.
11. Morgenstern, N. R., Tchalenko, J. S. Microscopic structures in kaolin subjected to direct shear; Géotechnique; Vol. 17, No. 4, 1967, pp. 309-328.
12. Potts, D. M., Dounias, G. T., Vaughan, P. R. Finite element analysis of the direct shear box test; Géotechnique; Vol. 37, No. 1, 1987, pp. 11-23.
13. Skempton, A. W. Residual strength of clays in landslides, folded strata and the laboratory; Géotechnique; Vol. 35, No. 1, 1985, pp. 3-8.
14. Stark, T. D., Eid, H. T. Drained residual strength of cohesive soils; Journal of Geotechnical Engineering – ASCE; 120(5), 1994, pp. 856-871.
15. Timothy, D., Hisham, T. Drained residual strength of cohesive soils; Journal of Geotechnical Engineering; Vol. 120, No. 5, 1994, Paper No. 909.