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The Evolution of Direct Simple Shear Testing: A Literature Review

Dan Bruton
Ecora Engineering & Resource Group Ltd., Vancouver, BC, Canada
David Randt
WSP Canada Ltd., Vancouver, BC, Canada

ABSTRACT
Prior to Kenneth Roscoe's work at Cambridge University, the only available shear testing device was the Direct Shear (DS) test, which had a significant limitation in that it did not permit rotation of the principal axes during shearing. In this test, the sample was forced to fail along a specified failure surface between the upper and lower parts of the shear box. In 1953, Roscoe improved the direct shear test with the addition of hinged walls. This test facilitated rotation of the principal axes, enabled simple shear, and did not force the soil to fail through a specified failure surface. Since then further advancements have been made in the evolution of shear testing. This paper provides a summary of the evolution from the 1800s to present day.

RÉSUMÉ
Avant les travaux de Kenneth Roscoe à l'Université de Cambridge, le seul appareil d'essai de cisaillement disponible était le Direct Shear (DS), un dispositif de cisaillement direct, qui présentait une limitation importante en ce qu'il ne permettait pas la rotation des axes principaux pendant le cisaillement. Ce dispositif forçait l'échantillon à se rompre le long d'une surface de rupture spécifiée entre les parties supérieure et inférieure de la boîte de cisaillement. En 1953, Roscoe a amélioré l'essai de cisaillement direct en ajoutant des murs articulés. Cette nouvelle méthode facilitait la rotation des axes principaux, permettait un cisaillement simple et ne forçait pas l'échantillon de sol à se rompre le long d'une surface de rupture spécifiée. Depuis lors, de nouveaux progrès ont été réalisés dans l'évolution des essais de cisaillement. Cet article résume l'évolution de ces essais des années 1800 à nos jours.

1 INTRODUCTION

The 1950s and 1960s were a key time in the development of soil mechanics particularly at Cambridge University where significant advances were being made in developing an understanding of soils and their plastic response to loading. Kenneth Harry Roscoe delivered the distinguished Rankine lecture in 1970 entitled "*The Influence of Strains in Soil Mechanics*" which was summarised in his 1970 paper. Tragically, Roscoe died that same year in a motor vehicle accident at the age of 55. His landmark paper provides a summary of two decades at Cambridge University in which significant advances were made in soil mechanics. This included the development of the theory of Critical State Soil Mechanics, the Cam Clay constitutive model and the Modified Cam Clay constitutive model. Key to the development of these models was the need to verify them with appropriate laboratory tests. Direct shear testing was commonplace, however, it had shortcomings in modelling representative shearing mechanisms. As such, Roscoe and his team at Cambridge developed laboratory test equipment that was capable of measuring soil response to shearing in a representative loading manner. This test was the "simple shear test". The following paper discusses the development of the simple shear test from the early days of direct shear testing up until Roscoe's testing apparatus. It then discusses the evolution of simple shear testing (including cyclic testing) and concludes with some interesting examples.

2 EVOLUTION OF SHEAR TESTING

2.1 1840-1950s: Direct Shear Test

The first soil-testing shear apparatus was developed by Collin (1846). In this test, a 40 mm square sample of clay was tested by loading it transversely until it failed in double direct shear (Saada and Townsend 1981). This apparatus is shown in Figure 1.

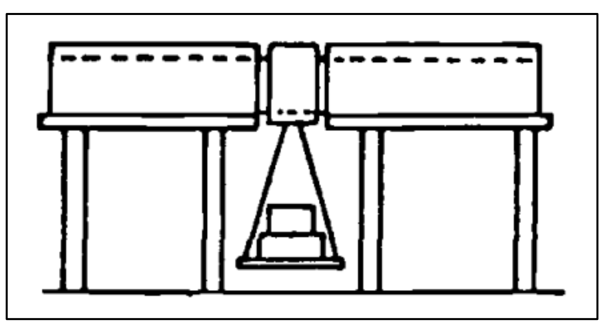

Figure 1. Double direct shear test developed by Collin (1846).

Krey, Terzaghi and Casagrande developed the direct shear test in the early 1900s (Saada and Townsend, 1981). This test involves placing the soil sample into a box with an upper part and a lower part. A normal force is applied to the top of the box and a shear force is then applied which causes the sample to fail at the plane of the intersection of the two boxes. This test is commonly used today in similar form to the test developed by Krey, Terzaghi and Casagrande. This test is commonly referred to as the "shear box" test or "direct shear test".

In 1937, Hvorsley conducted various tests on reconstituted clays using the shear box developed but with a rocking cradle incorporated (Hvorslev, 1937). This work was instrumental in the development of critical state soil mechanics as he showed that peak shear stress is dependent on both effective normal stress and void ratio at failure. The shear box apparatus used by Hvorslev is shown in Figure 2.

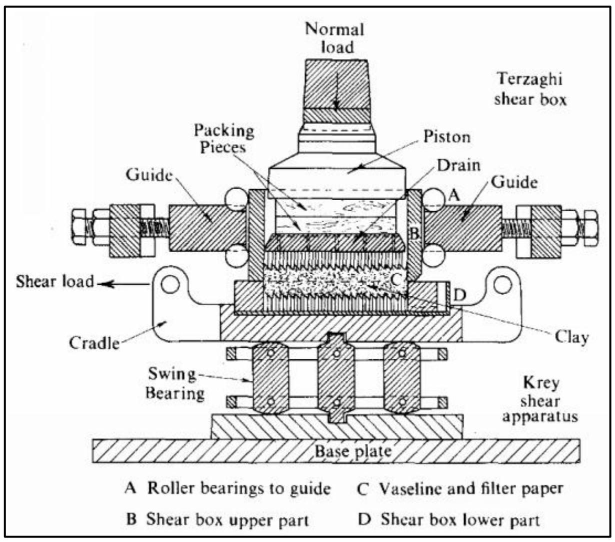

Figure 2. Shear box test used by Hvorslev (1937).

2.2 1950-1960s: The Birth of Simple Shear testing

2.2.1 Simple Shear Test (1953)

Although significant advancements were made between the mid-1800s and the 1940s, it was well recognised that there were deficiencies in the direct shear test. The main reason for this is that the test did not allow the principal axes to rotate during shearing. The shear box mobilises only a shear zone at the boundary between the two halves of the box, not representative of field conditions. Roscoe identified these limitations (and of conventional triaxial testing), which compel the principal axes of stress and of strain to coincide at all times on the boundaries of the soil sample (Roscoe, 1970).

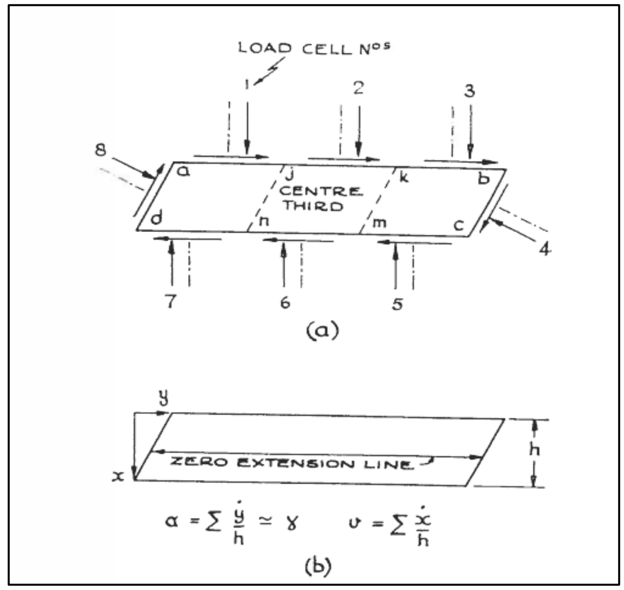

Figure 3. Schematic diagram of Roscoe simple shear apparatus showing (a) load cells, (b) strains with horizontal line of zero extension (Roscoe, 1970).

A simple shear apparatus was introduced, in which a rectangular or cylindrical sample of clay is mounted in a cell and subjected to an axial stress and to a shear in such a manner that the entire sample distorts without the formation of a single shearing surface. Originally discussed in Roscoe 1953, the leading and trailing surfaces of the soil were constrained by metal plates which were hinged in such a way that they forced the sample to deform in the desired manner. The simple shear test engages the whole specimen in the shearing process thus mimicking the stress regime to that of in-situ field conditions. A schematic diagram of Roscoe's simple shear apparatus is shown in Figure 3.

Roscoe's test involved the shearing of a cuboidal sample under plane strain conditions into a parallelepiped. Roscoe's test consisted of a square box that was 60 mm by 60 mm square by 20 mm high sample. The side of the apparatus comprised roller bearings that allowed the sample to deform at the top but remain stationary at the bottom. A vertical section from Roscoe's 1953 paper is shown in Figure 4.

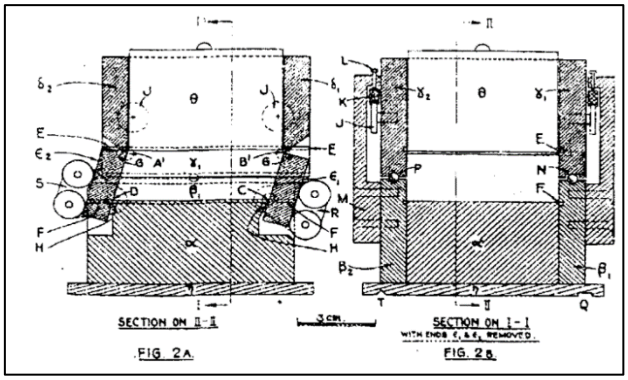

Figure 4. Vertical sectional elevation of the simple shear device (Roscoe 1953).

2.2.2 Direct Simple Shear Test (1966)

Bjerrum and Landva (1966) of the Norwegian Geotechnical Institute (NGI) developed the apparatus further with what is now known as the Direct Simple Shear test (DSS). The apparatus consists of a cylindrical soil specimen with cross-sectional area ranging between 20 cm^2 to 104 cm^2 and a typical height of between 16 mm and 22 mm (Vaid and Sivathayalan, 1996). The specimen is enclosed in a wire-reinforced rubber membrane which prevents horizontal extension (i.e. radial deformation), while allowing the specimen to deform vertically, in “simple shear”. An example of a modified-NGI DSS test is shown in Figure 5. Two main procedures are in use for the shear phase of direct simple shear tests: maintaining a constant vertical load during shearing; or maintaining the volume of the soil specimen constant by keeping the height of the sample constant. The former is considered to yield drained shear strength parameters, the latter undrained shear strength parameters.

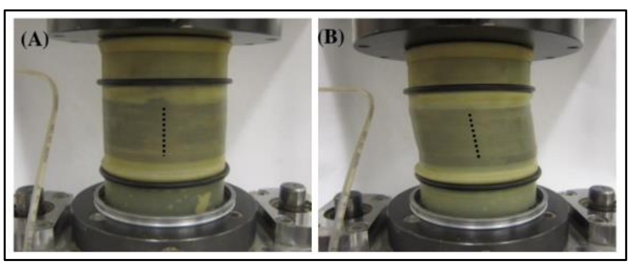

Figure 5. Modified NGI DSS test example. Photo A: After applying the seating pressure but prior to consolidation. Photo B: After monotonic shearing up to 20% shear strain (Soysa 2015).

2.2.3 Developments in the 1970s-2016

The shear testing devices used today are remarkably similar to those developed by Cambridge University (Roscoe 1953) and the Norwegian Geotechnical Institute (1966). The majority of developments since Roscoe 1953 and NGI (Bjerrum and Landva, 1966) have been related to the examination of the stress-strain distribution in the test rather than modifying the test apparatus. Through this time, there have also been various criticisms related to the use and validity of the DSS test. These are discussed below.

On 25 June 1980, a world symposium was held in Chicago on the “Laboratory Shear Strength of Soil” (Yong and Townsend, 1980). Two papers were published that were particularly critical of the DSS test as part of the conference proceedings:

Saada and Townsend (1981) challenged the ability of the DSS to test soils under plane strain conditions and cautioned against its use. Both the Roscoe and NGI devices claim conditions of plane strain and the NGI device also claims a uniform stress distribution. Saada and Townsend wrote that *“…simple shear devices…cannot claim to yield either reliable stress-strain relations or absolute failure values. At best they can be exploited in comparing descriptively similar soils…”.* La Rochelle (1981) was also extremely critical of the DSS test with his main claim being that the head platen has a tendency to rotate during the test. He writes in his 1981 paper that “*the author cannot find any real advantage to the use of the DSS device: it is not appreciably simpler to use than the triaxial apparatus; it does not yield a strength value comparable to the peak strength obtained in the triaxial test; it gives no reliable information on the shear or deformation moduli; even the volumetric moduli obtained in the NGI apparatus on samples of overconsolidated sensitive clays may be adversely influenced by the poor confinement of the reinforced membrane; and for the same reason, the value of the preconsolidation pressure obtained during the consolidation stage in that device can be seriously questioned”*

Furthermore, A Finite Element (FE) study was conducted by Dounias and Potts (1993) utilizing the Cambridge device to investigate stress and strain non-uniformities. Their results indicated that with increasing shear strain, there was an increase in stress and strain non-uniformity within the specimen. Fakharian and Evgin (1995) showed that direct shear (i.e. “shear box”) test results yielded similar results to DSS tests under both cyclic and monotonic loading.

However, there has been a definitive counter-argument to the criticisms of Saada and Townsend, La Rochelle, and others. In 1984 Budhu noted that the distribution of strains along the height of the specimen is fairly uniform for shear strains less than 5% (Budhu, 1984). In more recent years, Dabeet (2014) looked into the evaluation of stress strain non-uniformities using Discrete Element Method (DEM). A fairly uniform stress ratio distribution was observed near the central planes parallel and perpendicular to the direction of shearing. Some non-uniformities were noted near the top and bottom boundaries. It was concluded that the stress-strain relation from a simulated DEM simple shear model is in reasonable agreement with the conventional test.

In modern practise, the NGI direct shear test tends to be the preferred apparatus. The test method commonly followed is ASTM D6528 (Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils).

3 CYCLIC DIRECT SIMPLE SHEAR TESTING

Liquefaction became a major topic in soil dynamics following the Niigata, Japan, and Alaska earthquakes of 1964. The pioneering work of Seed and Lee (1966) with cyclic triaxial testing gave birth to the study of seismically-induced liquefaction, and the development of new laboratory tests for measuring liquefaction potential was of particular interest for following decade (Finn, 1981). Contributors to the evolution of cyclic simple shear include:

i. Cyclic simple shear (Cambridge): Peacock and Seed (1968); Finn et al., (1971);
ii. Cyclic direct simple shear (NGI): Moussa (1974); Youd and Craven (1975);
iii. Large-scale shake table testing: De Alba et al., (1976); and
iv. Multiaxial simple shear testing: Casagrande and Rendon (1978); Ishihara and Yamazaki (1980).

Peacock and Seed (1968), as well as Finn et al. (1971), were early contributors to the evolution of the cyclic simple shear apparatus in their investigations of sand under undrained cyclic shear testing, utilizing a modified version of the device used by Roscoe. Since the specimen is enclosed by a sealed rubber membrane, a sand specimen can be fully saturated with water by using back pressure, so the pore water pressure can be measured during undrained simple shear tests (Franke et al., 1979). The concept of constant volume drained testing, utilizing this apparatus, was later advanced by Pickering (1973) and Finn and Vaid (1977) in order to address membrane influences on excess pore pressure measurement (i.e. compliance, described in Section 3.1).

The performance of ordinary undrained shear tests using back pressure to fully saturate the specimen is not possible with the NGI direct simple shear apparatus. This is because excess pore water pressure and a resulting sufficiently high back pressure would lead to bulging of the reinforced rubber membrane (Franke et al., 1979). In order to apply cyclic shearing to a sample, the constant volume shear test was developed and is discussed further in Section 3.2.

Larger scale shake table testing was also devised during the evolution of cyclic simple shear. This was done in order to minimize the influence along the vertical boundaries of the sample-membrane interface (i.e. compliance). By increasing the plan area of the sample to dimensions of 2.2 m x 1.1 m for a 100 mm thick sample, only the central portion of the sample is instrumented and considered in the analysis of the test data, where uniform conditions are expected to exist (Jefferies and Been, 2015). This is done in an attempt to reproduce actual seismic ground shaking conditions (Chen et al., 2005).

Casagrande and Rendon (1978) experimented with a simple shear test apparatus in which cyclic shear stresses could be applied in multi-directional loading conditions, leading to the multi-directional simple shear device. This device incorporated two pneumatic cyclic loaders applied perpendicularly to one another (Ishihara and Yamazaki, 1980). However, a limited number of bi-directional testing programs on liquefiable soils have been conducted due to the difficulty in designing equipment (Kammerer, 2002).

More recent work, focused on the testing of dilatant sands, has been undertaken by Kammerer (2002) utilizing the U.C. Berkeley Bi-directional Simple Shear Apparatus (a modification of the NGI-type device). The apparatus was designed with the capabilities of both constant vertical load and constant vertical height boundary conditions, with the ability to perform tests of fully saturated samples with both reinforced and non-reinforced membranes (Kammerer, 2002). Secondly, the device accommodates a 4-inch sample diameter, and a height of approximately ¾-inch (diameter to height ratio of greater than five), limiting non-uniformity within the active regions of the sample (see Section 2.2.3).

The developments made between 1970 and 1980 refine the methodology for cyclic simple shear testing into predominantly two main testing techniques: undrained cyclic testing; and constant volume testing. The main distinction between the two test procedures is in the difficulty of sample preparation and time-consumption; undrained cyclic testing generally attributing to this. Another distinction between the two testing methods is the apparatus. At this point in time, the Cambridge device is being utilized for undrained cyclic testing, and the NGI device has been modified to carry out constant volume testing (Figure 6). However, as discussed below, each apparatus is eventually designed to enable testing on soil specimens under constant volume (Song et al., 2004).

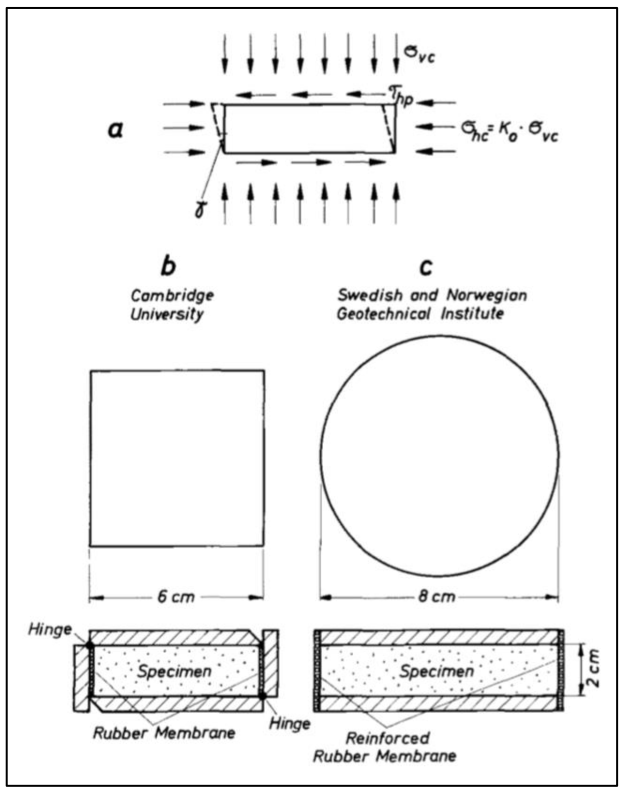

Figure 6. (a) Stress conditions in a direct simple shear device; (b) schematic of the Cambridge apparatus; and (c) schematic of the NGI apparatus (Franke et al., 1979).

3.1 Undrained Cyclic Testing

Utilizing the Cambridge device, the rigid walls and rubber membrane allow for undrained conditions, whereby back-pressure is applied to maintain saturation which enables a measurement of excess pore pressure during testing. However, the issue of compliance arises after the sample is consolidated to the desired confining pressure. Compliance occurs with changes in membrane thickness, membrane stretch in corners, and expansion of the confining frame as pore-water pressures increase (Martin et al., 1978). As pore pressures increase, there is the migration of a small amount of pore water to the lateral boundaries, in turn decreasing the volume of the grain structure, resulting in a lower pore pressure than perfectly undrained conditions.

Finn and Vaid (1977) discuss eliminating the effects of compliance from undrained testing and suggest the modification of the Cambridge device to accommodate constant volume simple shear liquefaction tests, where drained samples are tested under constant volume conditions (discussed in further detail below). Using dry or drained sand removes the time-consuming and difficult features associated with undrained tests and the errors that arise from compliance are nearly negligible for practical purposes (Finn and Vaid, 1977).

3.2 Constant Volume Cyclic Shear Testing

The performance of ordinary undrained shear tests using back pressure to fully saturate specimens is not possible with the NGI-type apparatus, as excess pore pressures and high back pressure would lead to bulging of the reinforced rubber membrane (Franke et al, 1979). Moussa (1974) utilizes the constant volume cyclic shear test to understand the shearing resistance of coastal sands to repetitive wave loading. In this test, the drainage boundaries remain open, and cyclic shearing is performed on dry sand. To achieve constant volume of the specimen, the vertical load is adjusted to maintain a constant height; any change in vertical load to accommodate a constant height is assumed to correspond to the change in pore water pressure of an equivalent test under undrained conditions. Cyclic shearing is achieved by the addition of a hanger system and hydraulic actuator which allows for a cycled shear force to be applied to the soil specimen (Dyvik et al., 1981). There still remains the issue of compliance. In 1975, Youd and Craven utilized the NGI DSS apparatus for cyclic testing and calibrated the wire-reinforced membrane to measure lateral stresses in sand specimens during cyclic loading in an attempt to further understand these affects.

4 PRACTICAL EXAMPLES OF DIRECT SIMPLE SHEAR TESTING

As Roscoe emphasised in his 1970 paper, the need for understanding the stress-strain response of soils is paramount. Roscoe described the simple shear test as a "versatile shear test which can impose a wide range of stress and/or strain paths" and hence, it is not surprising that it used commonly today.

The DSS test is particularly useful as it can be used to model representative failure surfaces in the field. Figure 7 (Budhu, 2011) demonstrates the applicability of the DSS test to various geotechnical engineering problems. It can be seen from this figure that the most appropriate shear test can vary for one failure surface depending on whether the shear strength of interest is within the active, intermediary, or passive zone of failure. This figure also demonstrates the applicability of the DSS test for retaining wall design, a pile resisting a tensile and compressive load, an embankment slope, and a spread footing. As discussed in the previous section, the cyclic DSS is also tremendously useful for modelling soil response to earthquake loading, wave loading and other vibratory effects. The following sections outline two examples of the application of cyclic and monotonic direct simple shear testing.

4.1 Seismic Response of Soils

As discussed earlier, the seismic response of soils became of particular importance following the 1964 Alaska and Japan earthquake. This caused widespread liquefaction and resulted in extensive damage to the city of Anchorage and Niigata. Today, cyclic direct simple shear testing is commonly used to assess the potential for a soils to liquefy or cyclically soften under seismic loading.

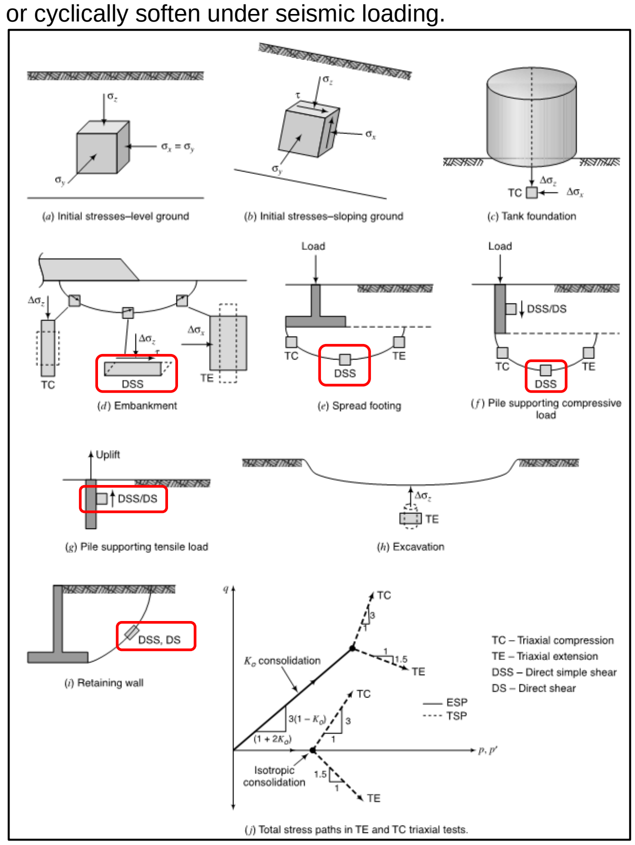

Figure 7. A few examples of practical cases with DSS tests circled in red (adapted from Budhu, 2011).

The cyclic DSS test comprises three main phases: consolidation stage; cyclic shear loading phase; and post-cyclic consolidation phase (Soysa, 2015). The vertical load is increased to a desired effective consolidation stress level, and generally kept for a duration of 30 minutes to a few hours. During the dynamic phase, cyclic shearing is applied at a constant amplitude through a motor controlled unit until a number of cycles is reached. For constant volume tests, the height of the sample is constant while the horizontal load is cycled. The waveform of choice can be entered into the system as well as the cycle count, data logging rate, frequency, and amplitude. In order to measure residual characteristics after cycling, the specimen is manually repositioned to the zero-strain level and reconsolidated to measure vertical effective stress and volumetric strain.

For this paper, we have presented a few findings from the work of Soysa (2015) who looked into the monotonic and cyclic shear loading response of natural silts to cyclic shear loading. Soysa undertook testing on three samples of silt from three different locations in the Lower Mainland of British Columbia. These tests utilised the constant-volume direct simple shear test (modified NGI apparatus). Some example plots from the three tests are shown in Figure 8.

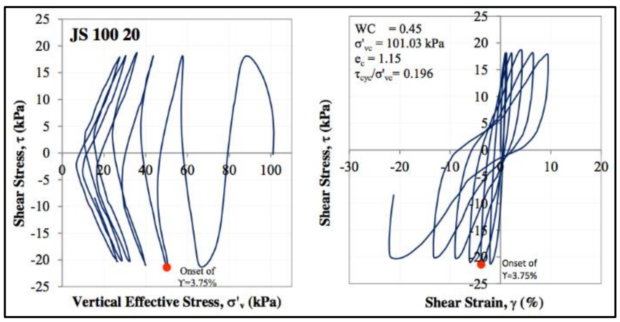

Figure 8. Silt specimen tested in constant-volume CDSS loading at a normally consolidated effective stress level of 100 kPa and CSR of 0.196. Specimen displays initial contractive behaviour during the initial loading cycles, followed by dilative and contractive responses during unloading and loading (Soysa, 2015).

4.2 Direct Simple Shear in Peat

Recent work by Long (2005) into the problems associated with laboratory testing of peats, has found that direct simple shear tests are one of the most useful laboratory tests in understanding the behaviour of peat as it relates to potential landslide conditions. Triaxial tests tend to yield higher angles of shearing resistance as compared to direct simple shear; this is attributed to the direction of shearing, which is generally parallel to the orientation of fibres in a direct simple shear test.

Grognet (2011) carried out a series of tests utilizing adapted versions of the NGI and Cambridge devices. The classical NGI device (i.e. wire reinforced membrane) and a modified unreinforced version of the NGI device, surrounded by a stack of rings to maintain zero lateral deformation were compared. It was found that the stacked rings created significant horizontal shearing resistances and did not provide reliable results. Furthermore, with the classical device, a simple shear state was not apparent since the shearing is applied at the top of the specimen and not at the sides (Grognet (2011). In this instance, anisotropy and fibrosity result in stress non-uniformity. Grognet subsequently developed a prototype of the Cambridge device to accommodate large peat samples (Figure 9).

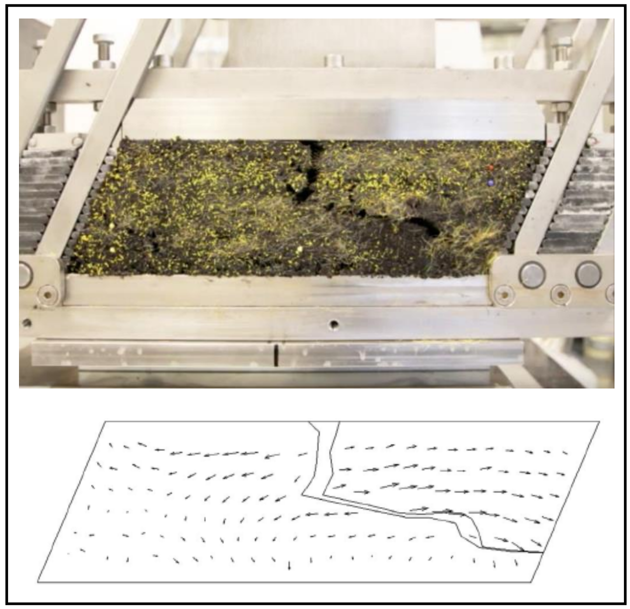

Figure 9. Specimen of peat having undergone monotonic simple shear with corresponding displacement vectors and rupture surface below, captured through Particle Image Velocimetry analysis (Grognet, 2011).

5 CONCLUSIONS

The Direct Shear (DS) test was the predecessor to the Direct Simple Shear (DSS) test with the main limitation being that it does not permit rotation of the principal axes and forces the soil specimen to fail along a specified failure plane. The DSS test appears to be a vast improvement on the DS test. It enables the principal axes to rotate, enables the soil to fail along any failure surface and invokes the condition of simple shear and is thus considered a more representative proxy for field conditions. Limitations have been raised by critics with respect to the ability of the DSS test to invoke plane strain conditions. They have also claimed that the existence of stress non-uniformities developed during shearing could render questionable results. Various researchers have investigated this further to gauge the extent of these effects.

Based on our literature review, the authors suggest that the idiosyncrasies of the direct shear test have been thoroughly investigated and the limitations addressed. The authors suggest that while the direct simple shear test has its limitations (together with all geotechnical testing methods), we consider it to be a good geotechnical test for measuring the shear strength of a soil provided that the designer is cognizant of these limitations.

We further suggest Figure 7 (Budhu, 2011) as a good reference for assessing the applicability of the DSS test to geotechnical engineering problems.

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