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DEVELOPMENT OF AN IMPROVED RING SHEAR DEVICE TO MEASURE LIQUEFIED SHEAR STRENGTH OF SANDY SOILS

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ABSTRACT

The shear strength of liquefied granular soils is a significant parameter in evaluating the safety of some earth structures, particularly those that are located in earthquake-prone regions. Measuring this strength in the laboratory is challenging since it is difficult to fulfill all of the conditions required to measure the liquefied shear strength with existing apparatuses, e.g., large shear strain/displacement, uniformity of stress and strain at large shear strain/displacement, undrained or constant volume shearing, direction of shearing relative to depositional planes, etc. In this study, we briefly review currently available laboratory devices used to measure this strength and conclude that the ring shear device complies reasonably well (and more favorably than other available test methods) with the essential prerequisites to measure the liquefied shear strength, despite some limitations. We then describe our development of an improved ring shear device to measure the liquefied shear strength that minimizes the limitations inherent in ring shear testing of sandy soils. The performance and advantages of ring shear testing is further demonstrated by the results of a preliminary ring shear test carried out by the improved apparatus.

Keywords: Liquefied shear strength, liquefaction, laboratory testing, constant volume, ring shear

INTRODUCTION

Liquefaction is an important issue for geotechnical engineers to evaluate during earthquakes. And predicting soil resistance during and after an earthquake is key to determining deformations of and potential damage to structures. During an earthquake, shaking-induced shear stresses generate positive excess porewater pressures in contractive saturated sandy soils. In response, the effective stress and the shear resistance decrease. Liquefaction of sloping ground occurs when the reduced effective stress crosses the available yield friction angle of the soil, i.e., the yield shear strength [s_u(yield)] is exceeded. Continued shearing then causes the shear resistance to drop to a minimum value, the liquefied shear strength [s_u(liq)]. If the gravitational (driving) shear stress is greater than s_u(liq), a liquefaction flow failure occurs. The liquefied shear strength occurs at relatively large deformations under a constant shear stress, constant effective confining stress at constant volume, and a constant rate of deformation (Castro and Poulos, 1977; Poulos, 1981).

In general two approaches are used to characterize the liquefied shear strength. One method is by back-calculating the shear strengths mobilized during liquefaction flow failures and correlating them to measured in-situ test parameters such as standard penetration resistance, cone penetration resistance or shear wave velocity (e.g., Olson and Stark, 2002). However, there are a number of uncertainties associated with this method, including strength heterogeneity, shape and location of the slip surface, uncertainties of material properties, pore pressure distribution, progressive failure, and three

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dimensional effects (Deschamps and Yankey, 2006), as well as potential drainage or void redistribution, hydroplaning, and the variability of in-situ measurements. The second option is to measure the liquefied shear strength directly with laboratory element tests. In this paper, we briefly outline the various testing devices that have been used to measure the liquefied shear strength and discuss their individual merits and limitations. We then describe the development of an improved ring shear device to measure the liquefied shear strength of contractive sandy soils that overcomes many of the limitations associated with other devices.

APPARATUSES USED TO MEASURE LIQUEFIED SHEAR STRENGTH

Principal requirements

The liquefied shear strength is achieved at large shear strains; hence any laboratory apparatus used to measure it should be able to operate consistently at large shear strains. Reliably measuring s_u(liq) also requires the ability to induce uniform stresses and strains in the test specimen so that stresses and strains measured on the specimen boundary represent the actual stresses and strains within the specimen. The sample should be large enough to develop a well-defined shear zone, far from its boundaries. The testing device should be able to consolidate the specimen (under drained conditions), but shear the specimen under undrained or constant volume conditions because the generation of excess porewater pressure is the key factor that triggers liquefaction. Another important attribute is for the device to shear the sample parallel to depositional planes in order to replicate the conditions exhibited by a large number of flow failures (Olson and Stark, 2002). In addition, it is preferable that the sample preparation requirements should not be very difficult. In the following paragraphs, we discuss the merits and limitations of several laboratory devices with respect to these requirements.

Rolling sleeve viscometer

The rolling sleeve viscometer (Johnson and Martosudarmo, 1997) is based on a principle of finite strain theory: an ellipse transforms itself into another ellipse if the internal deformation is homogeneous. Hence if a mass of debris surrounded by an elliptical cylindrical sleeve moves down a slope without being significantly deformed externally then the debris would be sheared uniformly. In the rolling sleeve viscometer a mass of soil is placed within a flexible sleeve such that it rests on a platform with a nearly elliptical shape. Then one end of the platform is raised so that the sleeve rolls down the slope and the terminal velocity of the sleeve is measured. The elliptical envelope doesn't slide, but rather rolls and deforms internally as it translates like a tractor tread so that the material inside the sleeve is sheared uniformly. The average shear stress within the mass can be computed knowing the slope angle, soil density, and ellipse dimensions, as well as the strain rate from the rolling velocity. At a particular ramp slope, the sleeve rolls continuously and the soil remains dispersed in the sleeve, i.e., it does not segregate into a two phase flow of water on top and a soil-water mixture at the bottom of the sleeve. This particular slope is used to calculate the properties of the flowing material and s_u(liq).

The rolling sleeve viscometer allows large strains to develop, is simple and inexpensive, can consolidate the soil specimen, has a constant volume, and the stresses and strains are approximately uniform within the specimen. However, the limitations of this test include: (1) the distributions of strain and stress during flow are difficult to determine; (2) preparing a uniform reconstituted specimen is not straightforward; (3) it is not possible to test undisturbed samples; (4) the effects of gravity and boundary conditions of the underlying rigid platform do not allow the sleeve to form a perfect ellipse; (5) end effects influence the average velocity and shear resistance; (6) shearing does not occur on depositional planes; and (7) since the sleeve is thin and flexible, the cross-sectional size and shape of the sleeve can change as the material within the sleeve contracts or dilates (which deviates from the principle theory of the method). Therefore, although its simplicity makes this test very attractive, the rolling sleeve viscometer does not reasonably satisfy all of the requirements for measuring s_u(liq).

Coaxial concentric-cylinder

Concentric-cylinders that rotate about a common axis have been used to measure the shearing behavior of concentrated suspensions of particulates in fluids (Bagnold, 1954; Savage and McKeown, 1983). Figure 1 schematically illustrates this device, which imposing a nearly uniform shear strain by minimizing the ratio of the radial dimension of the soil specimen (A) to the mean radius. In this device, the specimen (A) is bounded by inner (B) and outer (E) cylinders and an external normal load is applied radially by the pistons (D), which are guided by ball bearings (G) and moved by bellows (F). The inner shaft (C) rotates and shears the soil specimen.

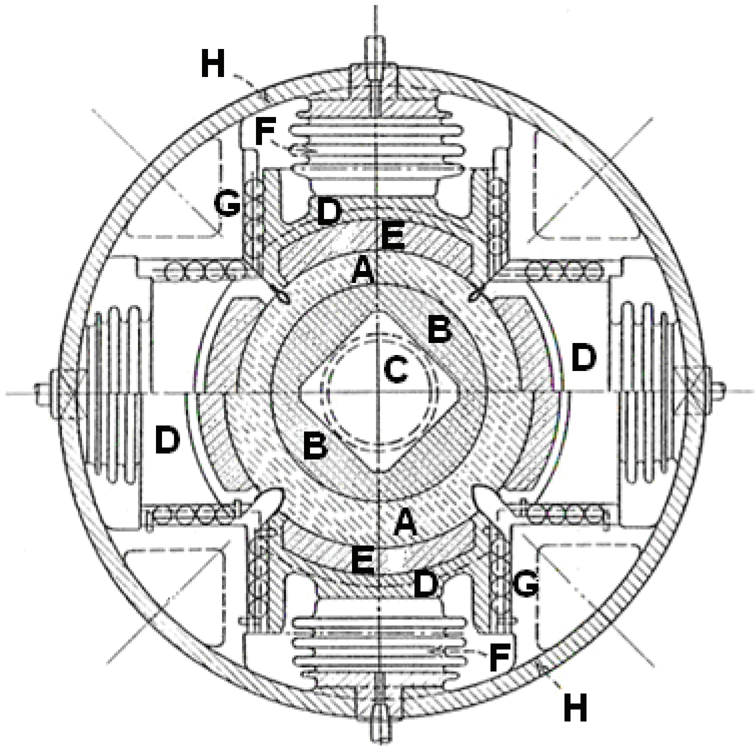


Figure 1: Schematic plan view of coaxial concentric cylinder apparatus developed by Arthur Casagrande and U.S. Engineer Office, Boston, MA (Hvorslev, 1939)

The coaxial concentric-cylinder shearing apparatus can achieve virtually unlimited strains, consolidate the soil specimen, perform constant volume tests, and uniformly distribute shear stress across the sample. But as can be seen in Figure 1, the device shears the sample on planes perpendicular to the depositional planes; and soil grains may extrude between the inner and outer cylinders, affecting volume change and shear stress measurements. Also the non-uniformity of shear strain at the top and bottom ends of the annular space is unavoidable and difficult to assess. Lastly, this device is difficult to build, it is difficult to apply equal normal load on each of the perpendicular outer cylinders, and both test setup and sample preparation are difficult, which makes testing undisturbed specimens virtually impossible.

Direct simple shear (DSS)

Undrained (Franke et al., 1979; Silver et al., 1980; Tatsuoka and Silver, 1981) and constant volume (Finn and Vaid, 1977) simple shear testing have frequently been used to investigate liquefaction triggering, but less frequently for measuring s_u(liq), which involves large-strain behavior. The merits of DSS include: (1) the capability to test either undisturbed and reconstituted specimens; (2) well-established sample preparation and testing methods; (3) shearing under stress- or strain-controlled conditions; (4) drainage is easily controlled; (5) rotation of principal stress axes; (6) shear stress are applied on depositional planes; (7) the area of shear remains constant; (8) side wall friction is eliminated; and (9) shear-induced lateral deformations are distributed fairly uniformly over the specimen height and cross section. However, the magnitude of strain that can be imposed on simple shear specimens is limited by the device itself and further limited due to the possibility of "pinching" at the specimen corners where acute angles form (Kramer et al., 2002). Furthermore, the lack of complementary shear stresses on the sides of the specimen requires that the moment produced by the horizontal shear stresses be balanced by non-uniformly distributed normal and shear stresses. As shearing continues, the non-uniformities of normal and shear stress distributions increase. Hence the post-peak shear resistance is reliable only to a limited extent.

Triaxial shear

Triaxial is the most commonly used apparatus to measure liquefied shear strength because of its many merits, such as: (1) the ability to test both undisturbed and reconstituted specimens; (2) well-established sample preparation and testing methods; (3) shearing under stress- or strain-controlled conditions; (4) controlled drainage; and (5) ability to apply a stress state that closely approximates the actual stress state under a foundation or earth structure.

On the other hand, there are several issues that limit this test's suitability for measuring s_u(liq) (Bishop et al. 1971; Sassa, 1992). The main drawback of the triaxial device is the limited available shear displacement. This limitation can lead to incomplete particle reorientation and/or breakage, making it difficult (if not impossible) to measure s_u(liq) for medium dense and dense sands (Chandler, 1985; Luzzani and Coop, 2002; Coop et al., 2004). In addition, sample bulging at larger strains (and the resulting increase in specimen cross-section) leads to potential errors in measuring s_u(liq) because of the uncertainty in the actual specimen shape, just as the conditions are of greatest interest (Kramer et al., 1999). These irregularities in sample shape cause non-uniform stress distributions, making it difficult to determine void ratio changes as well as the shear surface area and location. These latter uncertainties can lead to errors in computing the stress on the shear surface (Hvorslev and Kaufman, 1952; Shoaei and Sassa, 1994). Furthermore, the maximum shear stresses induced in the triaxial device occur on planes inclined to the generally horizontal depositional planes. The triaxial test also does not allow the continuous rotation of principal stress axes that occurs during actual flow failures (Kramer et al., 2002). Lastly, restraint exerted by the rubber membrane induces indeterminate forces which are most important when the deformations are large and external forces are small, i.e., when measuring s_u(liq) (Hvorslev and Kaufman, 1952).

Ring shear

In a ring shear test, a ring shaped specimen is confined between outer and inner rings and is sheared at its bottom (or top or mid-height) surface. A fixed plate on the top (or bottom) surface measures the resistance of the soil specimen against shearing. Figure 2 illustrates this mechanism. Comparatively, the ring shear device is the best suited to measure s_u(liq). The key points which lead to this conclusion are summarized as follows.

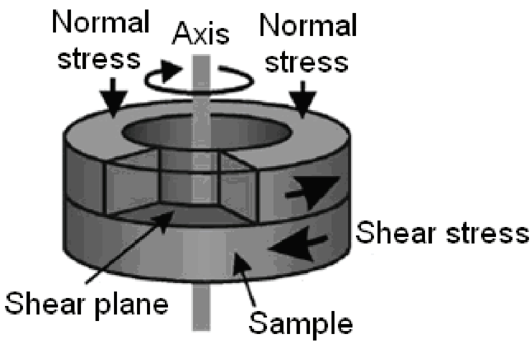


Figure 2: Shearing mechanism in a ring shear test

- Ability to shear a sample uninterrupted to virtually unlimited strains.
- Simple and well-established preparation methods for reconstituted specimens.
- Capable of applying known shear stresses on a horizontal (depositional) shearing plane.
- Ability to rotate principle stress directions.

- Ability to consolidate a specimen under drained conditions.
- Ability to accurately track volume changes because changes occur only in one dimension.
- The device's boundaries do not concentrate the deformations (Iverson et al., 1997), in contrast to direct shear and DSS devices.
- The cross sectional area of the shear plane remains unchanged during shearing.
- The geometry of the test specimen remains unchanged during shearing (Healy, 1963). (In contrast, the specimen in a triaxial test changes from a cylinder to nearly an oval.)

However, like any other testing method, the ring shear test is not perfect and there are some issues and limitations associated with this test, including non-uniform stress and strain distributions, soil extrusion, difficult undrained testing procedures, and wall friction.

Non-uniform stress and strain distributions

In a ring shear test, shear strain increases with radius; therefore, failure occurs progressively. This effect can be reduced by decreasing the annulus width, but this, in turn, increases the significance of the wall friction (Scarlett and Todd, 1969). Alternately, strain rate and progressive failure effects can be minimized by reducing the ratio of the outside to inside ring diameters. However, this ratio is practically limited by the apparatus size. That is, a large ring diameter requires a large torque to shear (rotate) the sample and a large loading system to apply the desired normal stress. Because of this limitation, the ring shear device is best suited to measure residual and liquefied shear strengths since at these states any progressive failure phenomenon is irrelevant (Hvorslev, 1939; Sembenelli and Ramirez, 1969; La Gatta, 1970; Bishop et al., 1971). Despite this, the ring shear is commonly used to determine the fully softened shear resistance in remolded clayey soils (Stark and Contreras, 1996) because the induced error is fairly small for optimal ring dimensions.

Soil extrusion

Soil may extrude between the upper (or lower) loading platen and the confining rings or through the split between the upper and lower rings (if present). This is a chronic problem in ring shear tests (Bishop et al., 1971; Tika et al., 1996; Iverson et al., 1998) and may cause more scatter in ring shear results than any other soil testing device (Vargas Monge, 1997). It also has been the limiting factor in continuing tests to very large displacements (Iverson et al., 1996). Soil extrusion affects the shear resistance measured by the normal loading plate as the top platen settles into the specimen container, and extruded soil that becomes trapped between the rings and top platen may increase the shearing resistance due to side friction (Stark and Vettel, 1992), especially if the normal loading plate is coupled to the upper confining ring to maintain undrained conditions (Sassa et al., 2003). Soil extrusion also prevents the accurate measurement of vertical sample deformation during shear.

As well as the aforementioned problems, excessive extrusion affects the normal stress distribution across the annular specimen. If soil is permitted to extrude during shearing, the normal stress will not become uniform – even at the residual state. Instead the normal stress will be lower than average at the location where extrusion occurs and soil will be pumped from a zone where the normal stress is larger than average. Thus, a residual condition is achieved with a normal stress distribution that is constant but not uniform. Furthermore, since the normal stress is lower at the edge of a specimen than at its center for any given average normal stress, the measured moment will be smaller than if the normal stress was uniform. This condition would cause the measured liquefied shear strength to be smaller than the true liquefied shear strength (La Gatta, 1970).

Undrained and constant volume testing

Generally the ring shear device geometry makes undrained testing very difficult. However, Sassa et al. (2003) recently developed an undrained ring shear device where the upper and lower confining rings are pressed together to maintain undrained conditions. In this device, the applied ring-to-ring pressure must always exceed the porewater pressure. In addition, a thin layer of vacuum silicon grease is applied to the upper and lower rings edges to maintain an undrained condition. The grease fills the microscopic defects in the rubber or steel and ensures watertightness. Sassa et al. (2003) then used pore pressure transducers to measure the shear-induced excess pore water pressure.

Alternately, Taylor (1952) introduced constant volume shear tests to measure peak undrained shear strengths, and he modified a direct shear device to perform constant volume tests. In constant volume tests, the decrease in applied vertical stress during shearing is assumed to be equal to the increase in shear-induced pore water pressure that would occur in an undrained test with constant vertical stress. Bjerrum and Landva (1966) and Dyvik et al. (1987) verified this assumption for direct simple shear tests, and Berre (1982) and Sasitharan et al. (1994) verified it for triaxial tests. Therefore, we anticipate that constant volume ring shear tests are equivalent to fully saturated undrained tests.

Wall friction

During consolidation and shear, wall friction may develop between the specimen and the inner and outer rings that reduces the applied normal stress and increases the apparent shear resistance of the specimen (Hvorslev and Kaufman, 1952). La Gatta (1970) indicated that the magnitude of vertical stress relief is independent on the normal stress and depends strongly on the amount of relative displacement between the soil and confining rings. During shearing, wall friction is fairly constant at small shear displacements; while at larger displacements, it varies considerably due to the changes in sample thickness. This, in turn, causes the effective normal stress acting on the sample to vary (Coop et al., 2004). Furthermore, shear-induced wall friction prevents a simple flow profile from forming (Scarlett and Todd, 1969). Wall friction generally has the smallest effect before attaining the peak stress ratio after reaching the phase transformation point (Vargas Monge, 1997). The significance of both types of wall friction can be reduced by designing a wider annulus; however, this would increase the strain rate effect.

DESIGNING AN IMPROVED RING SHEAR DEVICE

Following an extensive study of ring shear limitations (briefly described above), the authors designed and constructed an improved ring shear device at the University of Illinois, schematically illustrated in Figure 3. The specimen container has inner and outer diameters of approximately 20.3 cm and 27.0 cm, respectively, and a height of 5 cm; complying with ASTM D6467 requirements for ring shear testing. The ratio of the outer to inner ring diameter is 1.33. This diameter ratio results in an error of less than 3% at the peak shear stress due to strain non-uniformity (Hvorslev, 1939). The wide sample section (3.3 cm) also minimizes wall friction effects; however, the large sample size requires a large normal load (2300 kg) to achieve a normal stress of 700 kPa (the limit of the device). This normal stress range is sufficient to model nearly any sloping ground liquefaction problem. Normal load is applied by a lever arm (with a ratio of 10:1), transmitted to the sample by the central shaft (S), and measured by the lower load cell (L1). During compression and shearing, any normal load relieved by wall friction is measured by the upper load cell (L2). This value is later deducted from the readings of the lower load cell when calculating the effective normal load on the sample.

After applying the desired normal load and compressing the specimen, the sample can be sheared under either drained or constant volume conditions. A constant volume condition is maintained by tightening the nuts below the lower load cell, thereby preventing the upper loading platen from moving vertically. Shear load is applied by a computer-controlled servo-motor that is attached to a gear reducer (70:1 ratio). The motor applies a maximum torque of 2260 N·m corresponding to a shear stress of 483 kPa on the specimen. Shear is transmitted to the soil via serrated loading platens (UP and LP). Both strain- and stress-controlled tests can be performed because the servo-motor operates in both constant velocity and constant torque modes. However in the stress-controlled mode, the deformation rate is limited by the motor's maximum angular velocity. Furthermore, a brake implemented in the motor allows samples to be consolidated with an initial shear stress by holding that shear stress with the brake while the upper loading platen is locked into place, and then continuing the test by shearing under constant volume conditions. This simulates a static driving shear stress present in sloping ground, or below an embankment or foundation.

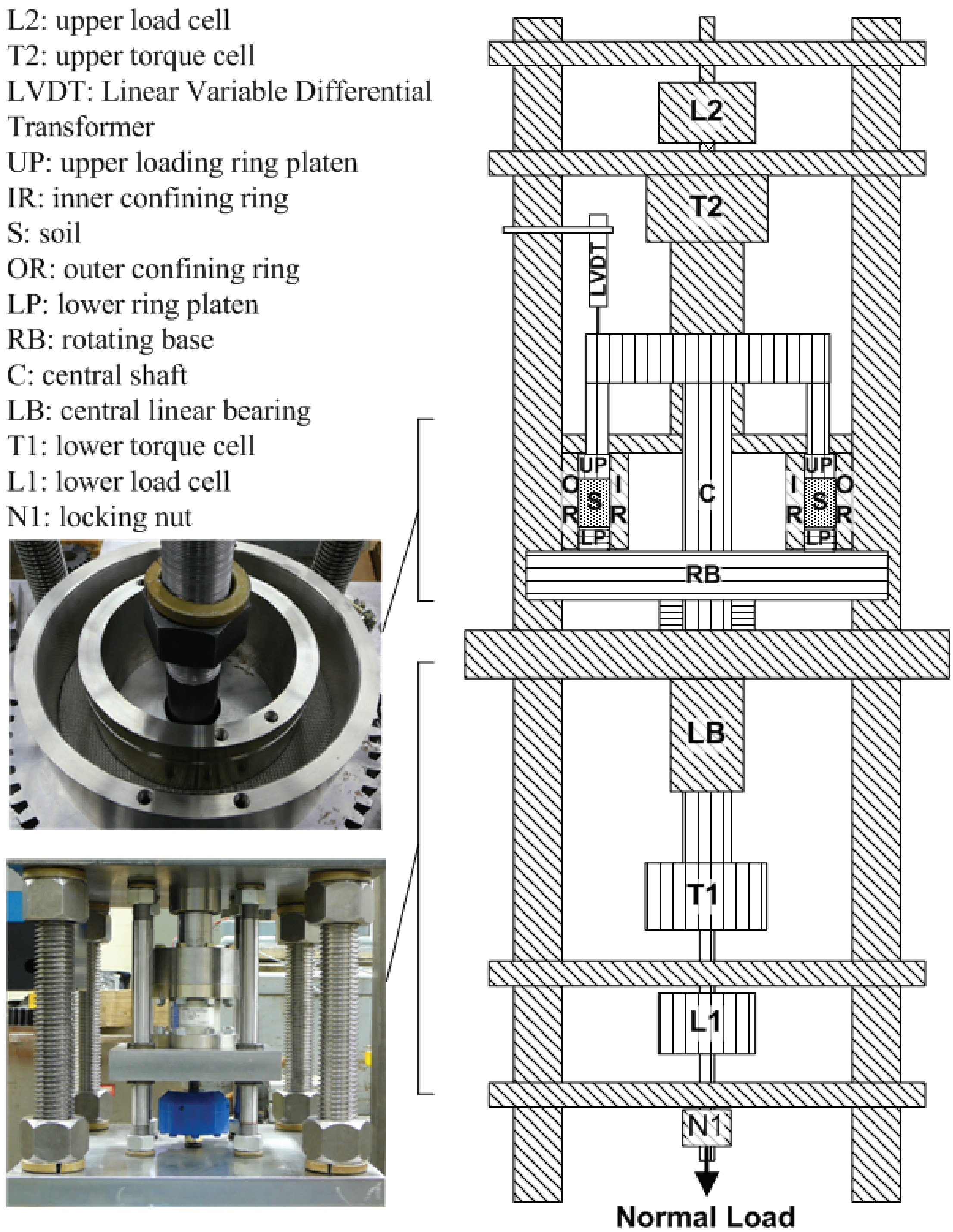
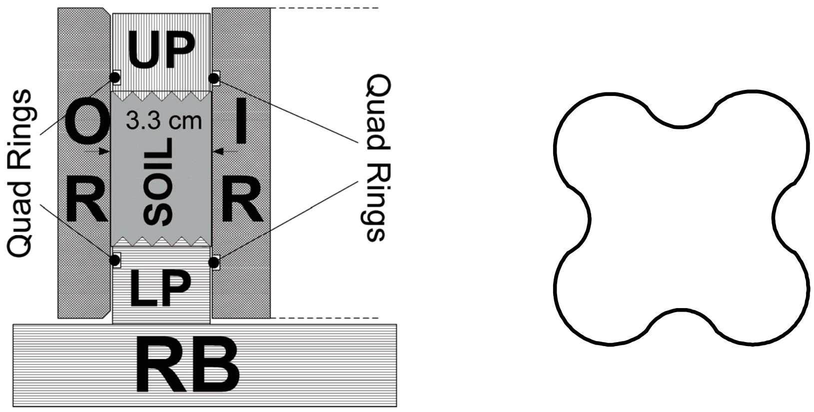


Figure 3: Schematic of the improved ring shear device developed at the University of Illinois. Rotating parts are hatched horizontally; vertically moving parts are hatched vertically; fixed parts are shaded.

In addition to static, uni-directional shearing, the servo-motor can almost instantly switch the direction of rotation. This combined with the large gear ratio of the gearbox allows us to perform cyclic tests with small shear strain amplitudes and high frequencies. Similar to a cyclic direct shear or DSS test, this mode of cyclic shearing properly simulates vertically-propagating, horizontally-polarized, shear waves during earthquake loading.

The upper torque transducer (T2) measures any shear-induced wall friction between the confining walls (IR and OR). This value is later deducted from the readings of the lower torque transducer (T1), which measures the total torque resisted by the specimen due to shearing and wall friction.

In order to minimize any soil extrusion during shearing, the seams between the annular loading platens (UP and LP) and the confining rings are sealed by quad-rings located in grooves on the inner sides of the loading platens and inner confining ring (IR) (Figure 4). If properly installed, the quad-rings can maintain fluid pressures greatly exceeding 700 kPa, potentially allowing us to perform undrained testing. To minimize friction developed along the quad-rings during shearing, we will coat them with a thin film of high vacuum silicon grease. We will measure any remaining friction in a calibration test with an empty soil container. Any measured quad-ring friction will be subtracted from the normal and shear forces measurements recorded during subsequent tests.



a) Specimen container **b) Quad-ring**

Figure 4: Cross sections of the specimen container and quad-ring

Non-uniform consolidation and soil extrusion potentially can cause the upper loading platen or the confining rings to tilt. Furthermore, if the forces on the upper loading platen and the central shaft transmitting the resisting torque have a small resultant force (i.e., they do not constitute a pure moment), then these elements may drift. A resultant force can be caused by non-uniform shear resistance over the entire specimen cross-section as well as excessive deflection of the normal loading lever. In this device, we used a central linear bearing (LB) to align the central shaft and upper loading platen, preventing potential misalignments. We also installed additional linear bearings to align the confining rings.

PRELIMNARY RESULTS

We performed an initial ring shear test on a siliceous Mississippi River Sand from Cape Girardeau, Missouri, USA. Dry sand was air pluviated into the ring shear container and the resulting initial void ratio was 1.038. We then consolidated the specimen to a normal stress of 395 kPa and a void ratio of 0.516. The normal loading disc was then locked in-place in order to prevent any further volume changes and the sample was sheared at a rate of 18.6 cm/min. Figure 5 presents plots of the stress – shear deformation and stress path.

In order to locate the shear plane and approximate its thickness, we performed another test with six paper strips inserted vertically at approximately 60 degree intervals in the ring-shaped specimen. Figure 6 shows one of the deformed paper strips after shearing the sample to 51 mm. The height of the paper strip was 29 mm. It can be inferred from Figure 6 that the shear plane developed at the mid-height of the specimen and was at least 5 mm thick. A second, essentially identical test on Mississippi River Sand was sheared to a displacement of 265 cm. Assuming that the shear plane thickness was approximately 5 mm, this displacement would correspond to a shear strain of 53000% - greatly exceeding the shear strains that other laboratory shear tests can achieve. In comparison, the triaxial compression test, most commonly used to measure liquefied shear strength, is reliable to a shear strain of only about 25%. Assuming a constant shear plane thickness of 5 mm throughout the test, 25% shear strain corresponds to a displacement of 1.25 mm. As illustrated in Figure 5a, the shear resistance of the Mississippi River Sand specimen is still decreasing at this displacement, and therefore is not at a steady state. In this test on Mississippi River Sand, a displacement of approximately 137 cm (or a shear strain of 27400%) is required to reach a steady state.

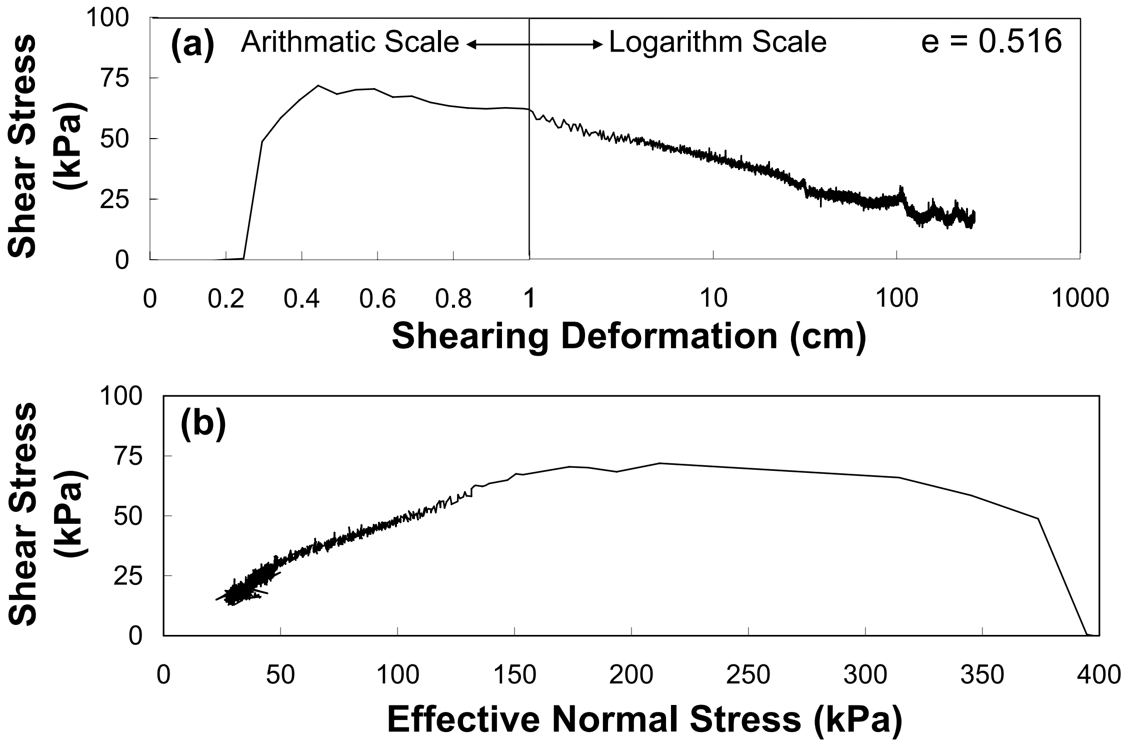


Figure 5: Results of an initial ring shear test performed on Mississippi River Sand. (a) shear stress-displacement plot; (b) stress path plot.

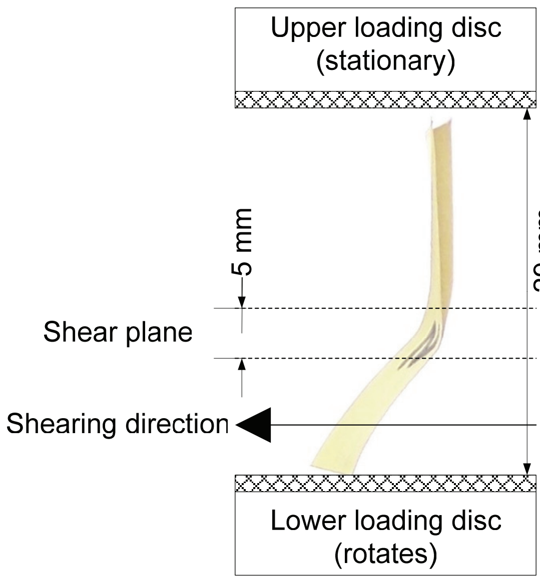


Figure 6: Deformed paper strip after sample is sheared to 51 mm displacement.

SUMMARY AND CONCLUSIONS

The liquefied shear strength is the shear strength mobilized at large displacement after liquefaction is triggered in saturated, contractive sandy soils. Therefore, any laboratory testing method used to measure the liquefied shear strength should be able to shear a soil to large displacements without significant stress or strain non-uniformities in an undrained or constant volume condition. Several laboratory devices have been used for this purpose, including the rolling sleeve viscometer, coaxial concentric cylinder, direct simple shear, triaxial compression and extension, and ring shear. Here, we critically review the merits and limitations of these devices with respect to measuring the liquefied shear strength. Based on this review, we conclude that the ring shear test is the most suitable method (of those reviewed) to measure the liquefied shear strength because: (1) it can reach virtually unlimited shear strains without creating substantial non-uniformities in stress and strain distributions at small to moderate strain levels; (2) it typically shears a soil on its horizontal depositional planes; (3) it allows the principal stresses to rotate in a manner similar to that expected under field conditions; and (4) the cross-sectional area and geometry of the specimen are constant during shearing. However, like all laboratory devices, the ring shear test has some limitations, such as stress and strain non-uniformities associated with some specimen dimensions, soil extrusion during shearing, difficulties in performing undrained testing, and friction that develops along the walls of the specimen confining rings.

Cognizant of these limitations, we designed and constructed an improved ring shear device at the University of Illinois that minimizes their impact. Specifically, we selected the confining ring dimensions to reduce stress and strain non-uniformities to a negligible amount at smaller strains, noting that these non-uniformities become irrelevant at larger strains. Any wall friction that develops along the confining rings is measured by an auxiliary load cell and torque cell, allowing us to correct the measured normal effective stress and shear resistance. In addition, we installed a locking device that holds the upper loading plate in place in order to perform constant volume tests, as well as watertight quad rings along the confining rings in order to perform undrained tests. We selected a specialized computer controlled servo-motor that allows us to perform ring shear tests under strain- or stress-controlled loading, cyclic loading tests, and tests on samples consolidated with a horizontal static shear stress.

Lastly, the preliminary ring shear test results that we performed demonstrated that the improved ring shear device developed and constructed at the University of Illinois can successfully measure the liquefied shear strength at a steady state of sandy soils under constant volume conditions. The liquefied shear strength measured in the preliminary tests was mobilized at a very large displacement. As such, most laboratory shear tests may not achieve the liquefied shear strength in a true steady state condition due to their limited shear strain capacity.

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