A Comparison Between the Shear Strength Measured with Direct Shear and Triaxial Devices on Undisturbed and Remolded Soils

Une comparaison entre la résistance au cisaillement mesurée avec appareils de cisaillement direct et triaxiaux sur les sols non remaniés et remoulés

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ABSTRACT: A comparison is presented between the shear strength measured with direct shear and triaxial devices based on the results from tests conducted on undisturbed and remolded soils. A series of consolidated-undrained (CU) triaxial tests and consolidated-drained (CD) direct shear tests were performed on undisturbed samples from the New Orleans area. These tests were conducted on soils ranging from low plasticity silts to organic fat clays. The results from the undisturbed samples showed that the drained friction angles obtained from the CU triaxial tests were considerably higher than those obtained from the CD direct shear tests. On the other hand, results obtained from remolded test specimens originating from a variety of locations showed almost no difference in the effective stress shear strength. The difference in the results can be explained in part by the fact that natural soils can have a preferred particle orientation or anisotropic fabric based on the deposition or formation of the soil. In the case of the New Orleans soils, the undisturbed samples exhibited evidence of horizontal deposition. In remolded samples, the soil is more much more homogeneous and isotropic, so every plane in the soil may be expected to have similar shear strength.

RÉSUMÉ : En utilisant des résultats de tests effectués sur des sols non perturbés et remoulés, une comparaison entre la résistance au cisaillement mesurée par cisaillement direct et avec des appareils triaxiaux est présentée. Une série d'essais triaxiaux consolidés non drainés et d'essais de cisaillement direct consolidés drainés ont été effectués sur des sols non remaniés de la région de la Nouvelle-Orléans. Ces tests ont été effectués sur des sols allant de vases de plasticité faible à des argiles organiques de haute plasticité. Les résultats des échantillons non perturbés ont démontré que les angles de friction drainés obtenus à partir d'essais triaxiaux consolidés non drainés sont considérablement plus élevés que ceux obtenus à partir d'essais de cisaillement direct. D'autre part, les résultats obtenus à partir de spécimens remoulés originaires de lieux divers n'ont montré pratiquement aucune différence dans la résistance effective au cisaillement. La différence des résultats peut s'expliquer en partie par le fait que les sols naturels peuvent avoir une orientation préférée des particules ou un tissu anisotrope basé sur le dépôt ou la formation du sol. Dans le cas des sols de la Nouvelle-Orléans, les échantillons intacts ont présenté des signes de déposition horizontale. Dans les échantillons remoulés le sol est beaucoup plus homogène et isotrope, de sorte que l'on peut s'attendre à ce que chaque plan du sol ait la même résistance au cisaillement.

KEYWORDS: direct shear, triaxial, shear strength, fully softened, remolded, undisturbed, shear strength measurement.

1 INTRODUCTION

The triaxial and direct shear devices have been historically used successfully to measure the peak shear strength of soils. In geotechnical projects, these tests are often used interchangeably to determine effective stress or drained shear strength parameters without regard to the potential difference in the results. A series of consolidated-undrained (CU) triaxial tests and consolidated-drained (CD) direct shear tests were performed on undisturbed samples from the New Orleans area. These tests were conducted on soils ranging from low plasticity silts to organic fat clays. The bulk of these tests were conducted as part of the reconstruction of the flood protection system, which was severely damaged by Hurricane Katrina in 2005.

The city of New Orleans is located on alluvial soils that are part of the delta formed by the sediments of the Mississippi River. According to Dunbar and Britsch (2008), the surficial soils were formed during the Holocene and consists of fine grained soils extending to about 17 m to 25 m deep in most of the area, while exceeding 46 m deep at some locations. Dunbar and Britsch (2008) stated that this layer is characterized by stacked and generally horizontal layering created by the deposition mechanism.

Numerous CU triaxial compression tests and CD direct shear tests were performed on undisturbed test specimens trimmed from 125 mm diameter tube samples to characterize the effective stress shear strength parameters of the soils in the greater New Orleans area. These test results were assessed to allow a comparison of the effective stress shear strength parameters for the undisturbed samples based on soil type, plasticity characteristics, etc. The tests conducted on the undisturbed tube samples were assessed based on the peak shear strength.

A series of direct shear tests and triaxial tests were also conducted on remolded soil specimens to determine the *fully softened* shear strength. The fully softened shear strength was defined by Skempton (1970) as the drained peak shear strength of a clay in its normally consolidated state. According to Skempton (1977), the fully softened shear strength can be measured on remolded normally consolidated specimens. Three different soils from various locations in the USA were tested to examine the difference in the fully softened strength parameters obtained from triaxial and direct shear test apparatuses.

2 PREVIOUS WORK

The direct shear and triaxial devices have been used for over 70 years to determine drained shear strength parameters of soils (Saada and Townsend 1981). These two devices have marked differences in the stress condition that is developed in the test specimen. Some of the biggest differences are: 1) strain boundary conditions, 2) failure plane orientations, and 3) principal stress orientation. In the triaxial device, the intermediate and minor principal stresses are equal and are normally specified at the beginning of the test. In the direct

shear device, the magnitudes of the intermediate and minor principal stresses are not known and are governed by the vertical stress applied and the strength properties of the soil being tested.

Progressive failure is the condition where the peak shear strength is not mobilized in every point of the failure plane at the same instance. This is caused by the non-uniform distribution of strain in the failure plane combined with the strain-softening characteristic of the soil. Some locations on the failure plane will mobilize the peak shear strength while others, having achieved more or less displacement, will mobilized a shear strength below the peak shear strength. For the direct shear device, investigators have reached different conclusions about the effect of stress concentrations in this device. Hvorslev (1960) measured horizontal displacements along the failure plane in a direct shear device and found that the displacements are not uniformly distributed, thereby causing progressive failure to occur. Alternatively, a finite element study of the direct shear box presented by Potts et al. (1987) showed that although stress concentration exist on the failure plane of the direct shear box, at the moment of failure the stresses on the failure plane are more or less uniform and the peak shear strength measured is not affected by progressive failure. For the triaxial device, stress concentration caused by the end restraints can influence the results. Research performed by Taylor (1941) showed that if the ratio of length to diameter is between 1.5 and 2.5, the effect of the stress concentration is negligible.

In the direct shear device, the orientation of the principal stresses on the failure plane varies during the shearing stage of the test and the final orientation is unknown. In the triaxial test, the major and minor principal stresses act on the horizontal and vertical planes and this orientation does not change during shear.

The orientation of the failure plane in the direct shear device is predetermined as being near the midpoint between the upper and lower halves of the shear box. In the triaxial device, the orientation of the failure plane is governed by the soil structure and the strength properties of the soil.

A literature review was undertaken to locate previous comparisons of the shear strength obtained using the triaxial and direct shear apparatuses. Skempton (1964) stated that the same effective stress shear strength parameters were obtained from tests conducted on eight specimens of Boulder Clay using the direct shear and triaxial devices. Casagrande and Poulos (1964) presented the results of CD direct shear and CD triaxial tests performed on compacted specimens of a lean clay which showed that about the same shear strength envelope was obtained with the two tests. Moon (1984) performed CD direct shear and CU triaxial tests on undisturbed samples of a fat clay and found that differences of less than one degree for the effective stress friction angle and less than 8 kPa for the effective cohesion intercept obtained from these two tests using the maximum principal stress ratio as the failure criterion. Thomson and Kjartanson (1985) performed CD direct shear tests and CD and CU triaxial tests on undisturbed samples of a lean clay and a fat clay and found that the results plotted on the same failure envelope. Abdel-Ghaffar (1990) compiled results from the literature where direct shear and triaxial tests were performed on undisturbed samples of the same soil. He concluded that the direct shear and triaxial devices provide comparable values for the effective stress friction angle and cohesion intercept. Maccarini (1993) performed CD direct shear and CD triaxial tests on a residual soil from Rio de Janeiro. For these tests, the tests specimens were oriented so that the failure plane in both devices coincided with the direction of stratification of the soil. The stratification of the soil had a dip angle of 25°. Based on the results obtained, Maccarini concluded that similar values of effective stress cohesion and friction angle are obtained from both tests if the stratification is taken into account.

Based on the results presented above, it can be seen that the available information in the literature is divided on whether these two devices will provide the same effective stress shear strength parameters. Investigators that have found agreement in the results did not state whether the soil tested had a preferred particle orientation or layering that could influence the results.

3 DATA COLLECTION AND RESULTS

3.1 *Undisturbed test specimens*

A subset of 63 CU triaxial test series and 146 CD direct shear test series was selected from the test results available from the New Orleans investigation. Each test series normally consisted of three individual tests conducted at different confining pressures. Only high quality tests were selected. The test results selected had to comply with the following requirements: 1) At least two test specimens were consolidated to stresses that were higher than the preconsolidation stress; 2) The end of primary consolidation was achieved during the consolidation stage of the test, 3) Index properties were available; 4) A peak deviator stress was reached for CU triaxial tests in less than 15% strain and a peak shear stress was reached for CD direct shear tests at a horizontal displacement less than 0.4 inches.

Since all the samples used were normally consolidated, the shear strength interpretation assumed that the effective stress cohesion intercept was zero. The least-squares method was used to obtain the corresponding effective stress friction angle.

Shown in Figure 1 are the values of the effective stress friction angles as a function of the Plasticity Index (PI) for the undisturbed New Orleans area test specimens for CD direct shear and CU triaxial tests. The trend lines shown on this figure are based on a statistical analysis performed by the authors. These lines are presented to better show the trend of the data and are not intended to be used as a correlation to predict friction angles. From this figure, it can be seen that the effective stress friction angle measured with the CU triaxial device is generally higher than that measured with the direct shear device. This difference was found to increase with increasing plasticity index of the soil. In general, the difference in friction angle ranged from about 2 degrees to 5 degrees.
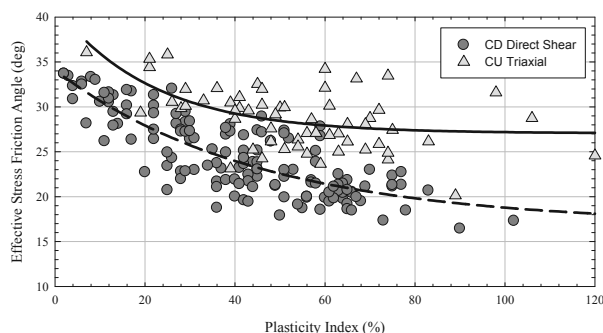

Figure 1. Relationship between effective stress friction angle and plasticity index for CD direct shear tests and CU triaxial tests on undisturbed samples.

3.2 *Remolded test specimens*

Three remolded clays were tested to allow a comparison of the fully softened shear strength measured in CD direct shear tests and CU triaxial tests. The index properties of these clays are shown are in Table 1. NOVA clay was obtained from a site in Northern Virginia in Fairfax County. Vicksburg Buckshot Clay (VBC) was obtained from the stockpile maintained at the Engineering Research and Development Center of the U.S. Army Corps of Engineers. It has been the subject of many research projects (Ladd and Preston 1965; Mitchell et al. 1965; Al-Hussaini and Townsend 1974). Colorado Clay is a lean clay (CL) from Silverthorne, Colorado.

To prepare the remolded samples, the soils were first soaked in water for at least 48 hours, and then processed through a No.

40 (425 µm) sieve. At this point, the samples were at a water content much greater than the liquid limit and were therefore air-dried to reduce the water content. The soil was considered to be at the desired water content when 23 to 25 blows using a Casagrande liquid limit cup were required to close the groove cut in the soil as specified in ASTM D4318-10.

Table 1. Soil index properties.

Soil	Specific Gravity	LL	PL	PI	Clay-sized Fraction
Colorado Clay	2.78	42	22	20	23.7
NOVA Clay	2.80	66	28	38	16.8
VBC	2.79	78	26	52	68.9

To perform CD direct shear tests, the test specimens were formed directly in the direct shear box using a spatula or "piped" from a pastry bag. Care was taken to form the test specimens without entrapping air-bubbles. Prior to shearing, the samples were consolidated under K_o conditions to vertical pressures ranging from 24 kPa to 288 kPa. The samples were then sheared slow enough to allow full dissipation of the pore pressures generated during shear using the criterion presented in ASTM D3080-11.

Triaxial test specimens were more difficult to form for tests at low effective consolidation stresses. At a water content equal to the liquid limit, the soil does not have the shear strength required to be formed into triaxial test specimens that can be installed in a triaxial cell. For this reason, a batch of soil was first consolidated in a batch consolidometer under K_o conditions to a vertical pressure of 38 kPa. The batch consolidometer used in this investigation is shown in Figure 2. After the batch of soil reached the end of primary consolidation, the sample was extruded from the specimen container, and triaxial test specimens were trimmed. The batch consolidometer formed samples that had a diameter of 15 cm, which allowed five to six 3.6 cm diameter test specimens to be trimmed. The triaxial test specimens were then installed in a triaxial cell, back pressure saturated, and consolidated to an all-around pressure ranging from 48 kPa to 483 kPa prior to shearing. The samples were sheared slow enough to allow equilibration of the pore pressures according to the criterion presented by Head (1986).

The results from the triaxial and direct shear tests performed on remolded samples are presented in Figure 3. The envelopes were clearly non-linear, and a power function was fit to the test results. The power function used was consistent with the format described by Lade (2010) (see Eq. 1).

$$\tau = a \cdot p_a \left(\frac{\sigma'}{p_a} \right)^b \tag{1}$$

with:

σ' = normal effective stress on the failure plane
p_a = atmospheric pressure in the same units as σ'.
a and b = curve fit parameters.

The results show that no significant differences were obtained in the failure envelope determined with the direct shear device and triaxial device for these remolded samples.

4 DISCUSSION

The difference in the results of the triaxial and direct shear tests on undisturbed and remolded samples can be explained, in part, by the difference in soil structure. The undisturbed tests specimens obtained from the greater New Orleans area were lacustrine and riverine alluvial deposits. These soils were deposited in horizontal layers, and could be expected to have a

preferential structure. Upon visual inspection, the New Orleans soils appear to be relatively homogenous. Distinct layering is often not discernible. Shown on the left side of Figure 5 is a section cut through an undisturbed New Orleans sample. The right side of Figure 5 shows the same sample after drying. The horizontal layers, which can represent planes of weakness, become evident after drying.
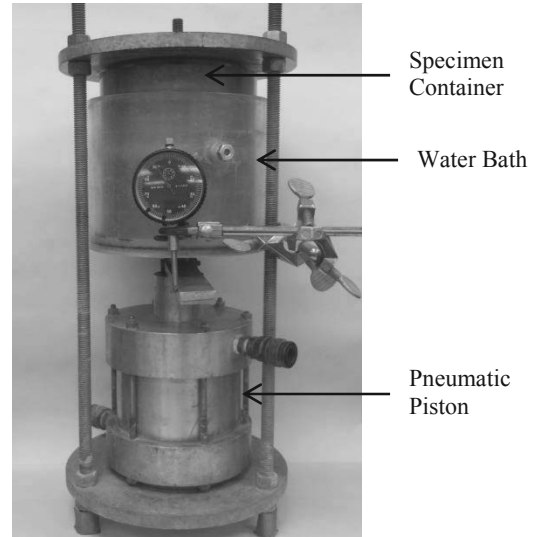

Figure 2. Batch consolidometer.

This horizontal layering can influence the shear strength measured using the direct shear device. In the direct shear device, the failure plane is horizontal. This forced failure plane can sometimes coincide with the natural layering or planes of weakness. In the triaxial device, the failure plane is not predetermined by the configuration of the device and horizontal planes of weakness would not be expected to control the measured shear strength. The difference in shear strength as a function of failure plane orientation has been documented by many investigators (Duncan and Seed 1966a; b; Filz et al. 1992).

Remolding soil destroys any previous layering or structure that might have been present, and the resulting sample is more or less homogenous. The influence of the failure plane orientation should be much less prevalent as compared to undisturbed samples. This suggests that fully softened shear strength (i.e. remolded normally consolidated peak shear strength) might be less dependent on the choice of the test apparatus than undisturbed shear strength.

5 CONCLUSIONS

The choice of using direct shear tests or triaxial tests to determine drained shear strength parameters can be important for natural soil deposits. Although these two different test methods can often provide similar results in some soil deposits, there is considerable evidence that direct shear tests provide much lower friction angles in riverine and lacustrine alluvial deposits than triaxial tests. A comparison of numerous CD direct shear and CU triaxial test results conducted on alluvial soils from the greater New Orleans area show that the friction angle determined from the direct shear apparatus is normally about 2 to 5 degrees lower than that determined using the triaxial apparatus. This can be attributed to the anisotropic shear strength characteristics of the alluvial soils.

The difference in the results of the two test devices is much less when remolded test specimens are used. The remolding process destroys the anisotropic fabric, and the shear strength parameters are not as dependent on the orientation of the failure plane. When fully softened shear strength parameters are desired, direct shear and triaxial test apparatuses appear to provide comparable results.
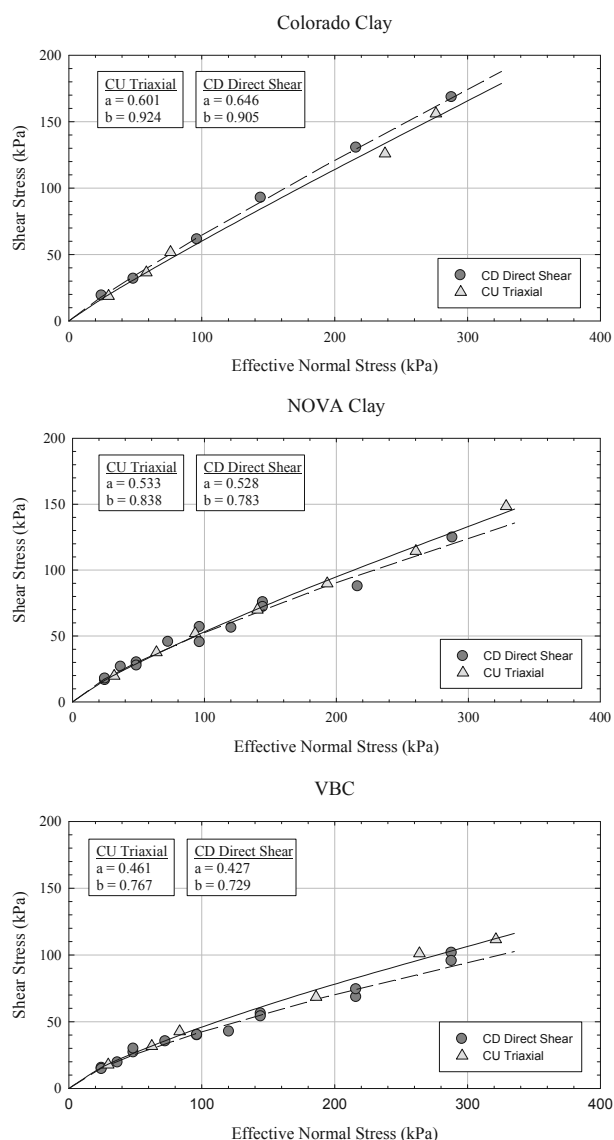
Colorado Clay

CU Triaxial
a = 0.601
b = 0.924

CD Direct Shear
a = 0.646
b = 0.905

● CD Direct Shear
△ CU Triaxial

NOVA Clay

CU Triaxial
a = 0.533
b = 0.838

CD Direct Shear
a = 0.528
b = 0.783

● CD Direct Shear
△ CU Triaxial

VBC

CU Triaxial
a = 0.461
b = 0.767

CD Direct Shear
a = 0.427
b = 0.729

● CD Direct Shear
△ CU Triaxial

Figure 3. CD direct shear and CU triaxial test results on remolded test specimens.
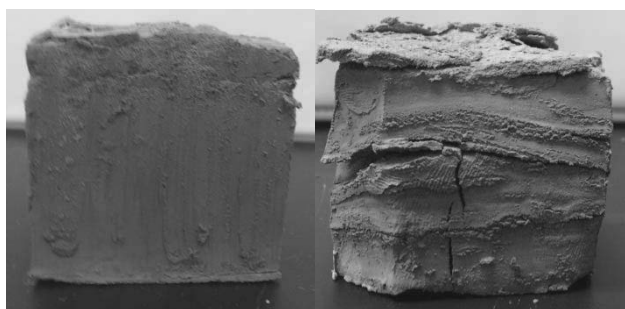
Figure 4. Undisturbed soil specimen before and after drying.

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