



CORRECTIONS EFFECT ON SHEAR STRENGTH PARAMETERS OF LOOSE OTTAWA SANDS

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Abstract: Triaxial tests are often used to determine the strength characteristics of soils subject to a wide range of stress paths and loading conditions. Triaxial testing involves many sources of error that could significantly affect shear strength parameters if not corrected. In this study, the errors associated with triaxial testing and the available correction techniques are thoroughly reviewed in a series of monotonic triaxial tests on loose Ottawa sand specimens. The significance of each correction on the triaxial compression test results and the achieved adjustments of the shear strength parameters and void ratio are presented and evaluated. It is found that complete negligence in making corrections accounting for these errors could result in an overestimation of as much as 44%, and 14.7° in the measurement of undrained and drained shear strength parameters, respectively. This will have significant influence on geotechnical engineering design and analysis.

Keywords: Triaxial testing, geotechnical engineering, shear strength, Ottawa sand, corrections.

1 INTRODUCTION

Laboratory shear tests conducted to understand soil behavior have been improved with the continuous advent of advanced testing devices. Triaxial tests on cylindrical specimens are often used for measuring the shear behavior of soils. Reliability of shear strength parameters for engineering applications and analysis depends on the accuracy and field resemblance of the triaxial shear testing results. In this study, monotonic triaxial compression tests are performed on loose Ottawa sand specimens to determine the volumetric response and shear behavior of the specimens' at large strains where a critical state is produced. Specially-designed moulds and platens are used to reduce end restraint effects and improve specimens' uniform deformation. Corrections are made to account for the volume change due to back pressure saturation (ASTM D4767, 2011) and membrane penetration (Baldi and Nova 1984), axial deformation due to bedding error (Sarsby *et al.* 1980), stress correction due to membrane resistance (ASTM D7181, 2011), and the change of specimen cross-sectional area during shear (Garga and Zhang 1997). The significance of each correction on the triaxial compression test results and the achieved adjustments of the shear strength parameters and void ratio are subsequently presented and evaluated.

2 EXPERIMENTAL METHODOLOGY

2.1 Triaxial Testing System

The triaxial tests of this research were conducted using an automated stress path triaxial compression testing system (SIGMA-1™ 5K model) manufactured by GeoTac, Texas, USA. The main components of the system include a triaxial cell, a loading frame, two electromechanical pressure pumps, and a data acquisition and control unit. The system also includes an external load cell, a deformation sensor, and three fluid pressure sensors. The axial load is applied by the loading frame in displacement-control (up to a rate of 25.4 mm/minute) or load-control (up to a maximum axial load of 10,000 N) modes. Soil resistance to the axial load is measured by a 2,000 N external load cell attached to the loading frame. All tests of this study were conducted using the displacement-control mode at a rate of 5%/hour. The axial deformation of the sample during shear was measured externally by a linear variable displacement transducer (LVDT) on the loading piston of the triaxial cell. Two electromechanical pumps (i.e. cell and pore pressure pumps) were used to control and measure the volume and pressure of the cell fluid and specimen's pore water. All sensors were calibrated at the commencement of the testing program.

2.2 Sand Properties and Samples Preparation

A clean, uniformly-graded Ottawa sand – classified as a SP according to the Unified Soil Classification System (ASTM D2487, 2011) - with round to sub-round particle shapes is used in the tests of this study. Sieve analysis was performed on the sand, and average mean particle size (D_{50}), coefficient of uniformity (C_u), and coefficient of curvature (C_c) of 0.22 mm, 1.71, and 1.07 were determined, respectively. Specific gravity of the sand particles (G_s), and maximum and minimum void ratios of respectively 2.65, 0.821, and 0.487 were measured following the ASTM standard procedures. Since the purpose of this study was to investigate the influence of different errors and multiple corrections on the testing of loose sands, all specimens were prepared by moist tamping. Cylindrical sand specimens were prepared with nominal diameters (D_s) of 38, 50, and 70 mm and height (H_s) to D_s ratios of unity to reduce non-uniformity at larger strains. As illustrated in Figure 1, two latex membranes of the same specimen diameter and with 0.3 mm thicknesses were smeared with a thin layer of silicon grease and placed over specimen caps in order to reduce specimen end effects. In order to minimize void ratio non-uniformities within the specimens, the under compaction technique introduced by Ladd (1978) was employed to achieve a relatively uniform density throughout the specimen height. A small vacuum (about 4 to 5 kPa) was subsequently applied by the pore pressure pump in order to provide temporary confinement and hold the specimen in place during dismantling of the mould while the actual specimen height (H_o) and diameter were measured in order to determine its initial volume (V_o) and thus initial void ratio (e_o). The cylindrical triaxial cell was then assembled and placed in the load frame, filled with de-aired water, and the vacuum pressure was replaced by an external cell pressure of 10 kPa. As complete saturation of the specimen was required to ensure accurate volume change and pore pressure measurement, carbon dioxide (CO_2) was first percolated through the specimens followed by flushing with water. The saturation procedure was proceeding with a backpressure saturation phase as recommended by Black and Lee (1973) until a pore water pressure parameter, B of at least 0.97 was achieved in all specimens.

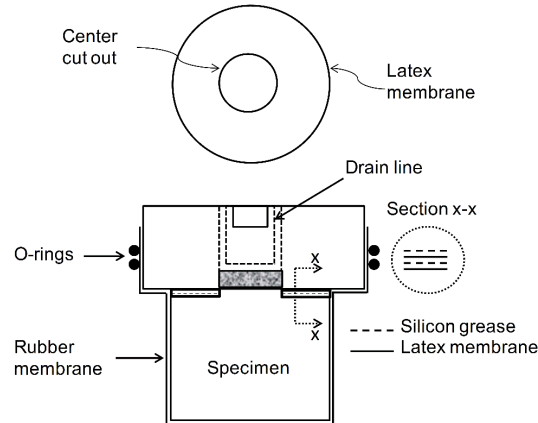


Figure 1: Procedure of developing lubricated and enlarged end platens

2.3 Consolidation and Shearing Phases

Isotropic consolidation commenced after the completion of specimen saturation by increasing the confining pressure to the target isotropic consolidation stress (p'_c) while recording specimen volume change for calculating consolidation void ratio (e_c) and relative density (D_{rc}). The specimens were sheared following isotropic consolidation. During shear the total cell pressure was kept constant while advancing the axial loading piston on the specimen cap at a constant strain rate of 5%/hour up to an axial strain of 30%. The shear strain rate was chosen based on ASTM D4767 (2011) and ASTM D7181 (2011) guidelines to ensure pore pressure equalization during undrained shearing and complete excess pore pressure dissipation during drained shear. Table 1 summarizes the specifications of the conducted tests.



Table 1: Specifications of the triaxial compression tests in this study

| P' _c (kPa) | 70mm | | | 50mm | | | 38mm | | |
|--------------------------|----------|----------------|---------------------|----------|----------------|---------------------|----------|----------------|---------------------|
| | Test No. | e _c | D _{rc} (%) | Test No. | e _c | D _{rc} (%) | Test No. | e _c | D _{rc} (%) |
| 500 | MT-1D | 0.771 | 15 | MT-9D | 0.761 | 19 | MT-17D | 0.76 | 18 |
| 300 | MT-2D | 0.779 | 13 | MT-10D | 0.769 | 16 | MT-18D | 0.766 | 16 |
| 200 | MT-3D | 0.785 | 11 | MT-11D | 0.773 | 14 | MT-19D | 0.775 | 14 |
| 100 | MT-4D | 0.797 | 7 | MT-12D | 0.786 | 10 | MT-20D | 0.786 | 10 |
| 500 | MT-5UD | 0.775 | 14 | MT-13UD | 0.769 | 16 | MT-21UD | 0.766 | 16 |
| 300 | MT-6UD | 0.782 | 12 | MT-14UD | 0.775 | 14 | MT-22UD | 0.773 | 14 |
| 200 | MT-7UD | 0.791 | 9 | MT-15UD | 0.785 | 11 | MT-23UD | 0.784 | 11 |
| 100 | MT-8UD | 0.797 | 7 | MT-16UD | 0.795 | 8 | MT-24UD | 0.794 | 8 |

3 CORRECTIONS FOR TRIAXIAL COMPRESSION TESTS

3.1 Saturation Phase and Volume Change

In conventional triaxial tests, e_c is calculated based on the initial specimen dimensions taken before assembling the cell and the void ratio changes occurring during backpressure saturation and consolidation. The correct assessment of this void ratio is particularly important in the critical state testing of loose sands because of the higher sensitivity of the critical state line to void ratio variations. The sample volume changes during flushing and backpressure saturation can be estimated by the volume change of the cell fluid or by measuring the axial and radial deformations of the specimen using specialized sensors. Imaging techniques using either a high resolution camera or a three-dimensional laser scanner are also utilized in some studies.

As described earlier, saturation of the moist tamped specimens in this study was accomplished by flushing the samples with CO₂ followed by de-aired water, and then applying back-pressure. Since the purpose of this study was to investigate the effects of measuring errors and corrections on loose sands and critical state testing, all specimens were prepared at $e_o = 0.821$, corresponding to a relative density of 0%. Volume changes occurring during backpressure saturation were estimated by measuring the axial strain (ϵ_a) of the specimen while making contact between the axial loading shaft and the specimen top cap after saturation, and calculating the radial strain (ϵ_r) and thus the volumetric strain (ϵ_v) of the specimen from its Poisson's ratio ($\nu = -\epsilon_r/\epsilon_a$). This procedure is described by the following relationships:

$$[1] \quad \epsilon_v = \epsilon_a + 2 \epsilon_r = (1 - 2\nu)\epsilon_a$$

$$[2] \quad \Delta V_s = \epsilon_v V_o = (1 - 2\nu) \epsilon_a V_o = (1 - 2\nu) \Delta H_s A_o$$

Where A_o is the initial cross sectional area of the specimen, and ΔH_s is the specimen's height change during saturation. An average Poisson's ratio of 0.34 was obtained for all specimens from specimen deformations measured during isotropic consolidation. The calculated ΔV_s indicated that void ratio decreased by an average of 1.1% (0.008 - 0.01) following back-pressure saturation which corresponds to about 2.4% to 3.0% in terms of relative density changes. Accordingly, neglecting saturation volume changes could lead to an overestimation of the specimens' void ratio and eventually an incorrect critical state line. This could further lead to about 2 - 3% underestimation of the undrained critical strength of the soil, $s_u(\text{critical})$ or effective friction angle (ϕ'_{cs}) resulting from the inaccurate cross-sectional area of the specimen before shear.



3.2 Membrane Penetration and Volume Change

In triaxial tests on granular soils, volume change due to membrane penetration occurs when the latex membrane penetrates into the surface irregularities of the specimen with increasing of the effective minor principal stress (σ'_3), while the membrane tends to return to its original position when σ'_3 is reduced. The amount of the resulting volume change is equal to the difference between the total volume of water driven out of the sample and the actual volume change of the soil skeleton. This phenomenon was first recognized by Newland and Alley (1957) and since then it has been of considerable interest for many researchers (Raju and Sadasivan, 1974; Baldi and Nova 1984; Nicholson *et al* 1993; Ansal and Erken 1996; Zhang 1997; Sivathayalan and Vaid 1998). In a drained triaxial test, σ'_3 remains constant and thus membrane penetration is negligible, whereas in an undrained triaxial shear test σ'_3 could change substantially as a result of shear-induced pore water pressure. The amount of membrane penetration is a function of many factors including σ'_3 , grain size, grain shape, gradation, density of the sample, the surface area of the sample in contact with the rubber membrane, and the characteristics of the rubber membrane such as its thickness and extension modulus (Raju and Sadasivan 1974).

Several methods are developed to account for the volume changes due to membrane penetration (ΔV_m). For example, Baldi and Nova (1984) investigated the membrane penetration in triaxial tests and found that ΔV_m depended strongly on D_{50} , σ'_3 , and the diameter of the specimen (D_s) as well as the membrane characteristics. Based on their analysis, a quantitative correction was developed to account for membrane penetration in a typical triaxial test as below:

$$[3] \Delta V_m = \left(\frac{D_{50}}{2 \times D_s} \right) \times \left[V_o \times \left(\frac{\sigma'_3 \times D_{50}}{E_m \times t_m} \right) \right]^{\frac{1}{3}}$$

Where E_m is the Young's modulus of the membrane material, and t_m is the thickness of the membrane. According to Eq. (3), the amount of ΔV_m in an undrained test mainly depends on σ'_3 , with a higher σ'_3 producing larger membrane penetration. Nicholson *et al.* (1993) found that the influence of sample density on membrane penetration was relatively small in comparison to the influence of D_{50} . Zhang (1997) studied the effect of membrane thickness on the amount of membrane penetration for two sands with different initial relative densities and found that membrane thickness significantly affected the amount of penetration in both sands. The thinner the membrane the higher the volume change was due to membrane penetration.

The amount of membrane penetration in this study is calculated using Eq. (3) as it accounts for most of the factors that affect membrane penetration. Correction for membrane penetration during isotropic consolidation was considered in all of the tests performed in this study by correcting the recorded volume change after consolidation and accordingly e_c . D_{50} of the tested sand, t_m , and E_m of the rubber membrane were measured respectively as 0.22 mm, 0.3 mm, and 1,350 kPa. The change in e_c due to membrane penetration was insignificant with an average of 0.36% (0.002 - 0.003), corresponding to about 0.6 to 0.9% changes in D_{rc} . This can be attributed to the fine gradation of the tested sand that limited the amount of membrane penetration into the surface irregularities of the specimen. During undrained shearing, specimen volume was kept constant throughout shearing by closing all the drainage lines. On the other side, the increase in shear-induced excess pore water pressure pushed the membrane out of the voids (or into the voids if the excess pore water pressure had decreased). This depends on the water modulus which is greatly affected by the degree of specimen saturation and therefore the actual effect of membrane penetration on pore water pressure generation was insignificant due to the slightly incomplete saturation (e.g. $S_r < 100\%$, $B = 0.97$). Note that the effect of membrane penetration on pore pressure response merely inhibits perfectly undrained shearing and it is not a measuring error as the actual shear-induced pore water pressure is continuously measured throughout the experiment.

3.3 Effects of End Restraints

A sand specimen will ideally deform as a right circular cylinder throughout a triaxial compression shear test with no boundary restraints, but it often exhibits bulging deformation as a result of friction at the specimen ends (Bishop and Green 1965). Specimen bulging produces non-uniform stresses and strains in a triaxial specimen which could significantly affect the measured strength, strain-softening, pore pressure or volume change behavior of a soil specimen particularly at large deformations associated with critical states. Different methods have been pursued to reduce the effect of specimen boundaries, but the lubricated end platens technique developed by Rowe and Barden (1964) has been the most effective method (Zhang 1997). As illustrated in Figure 1 enlarged and lubricated end platens were employed in the experimental work of this study to allow free radial expansion of the specimen and minimize the bulging deformation of the specimens during shear. The enlarged end platens were designed to accommodate the radial expansion of the specimen at shear strains of up to 30%. The slenderness or the height to diameter (H_s/D_s) ratio of a specimen is another factor that affects the bulging deformation. Bishop and Green (1965) illustrate that specimens with $H_s/D_s = 1$ and lubricated ends could deform nearly uniformly during drained shear, while more slender specimens ($H_s/D_s = 2$) displayed a bulging deformation irrespective of end restraints. Therefore, it was decided to adopt a slenderness ratio of unity along with lubricated and enlarged end platens to minimize the effects of specimen end restraint and allow for uniform specimen deformation and homogeneous stress distribution throughout the triaxial shear tests. That is particularly necessary for critical state testing which requires shearing to large shear strains. Accordingly, specially designed split moulds and hardened stainless steel end platens were constructed and used for preparing specimens that would accommodate enlarged platens. As a result homogeneous specimen deformations were obtained at the shear end of 30% strain.

A series of pilot tests were conducted on 50 mm specimens without lubricated platens and the results were compared with the production experiments in order to quantify the improvements gained by enlarging and lubricating the platens at large axial strains. Two undrained triaxial compression tests were performed for each case at $p'_c = 100$ kPa and 300 kPa corresponding to $D_{rc} = 8\%$ and 14% , respectively. The stress-strain responses and the mobilized friction angles (ϕ'_{mob}) are compared in Figure 2. According to this figure, the final deviator stress (q) and ϕ'_{mob} reduced by an average of 13% and 2° with the employment of enlarged and lubricated end platens. This reduction occurs as friction at specimen boundaries is reduced which leads to more uniform specimen deformation and stress distribution within the specimen. We also observed that the shear-induced excess pore pressure was slightly increased with lubricated ends, further reducing the undrained deviator stress. Accordingly, an average overestimation of about 10% in the measurement of undrained critical strength, $s_u(\text{critical})$ was calculated if the platens were not lubricated. These results are further supported by those observed by some other investigators (Olson and Campbell 1964; Ueng *et al.* 1988).

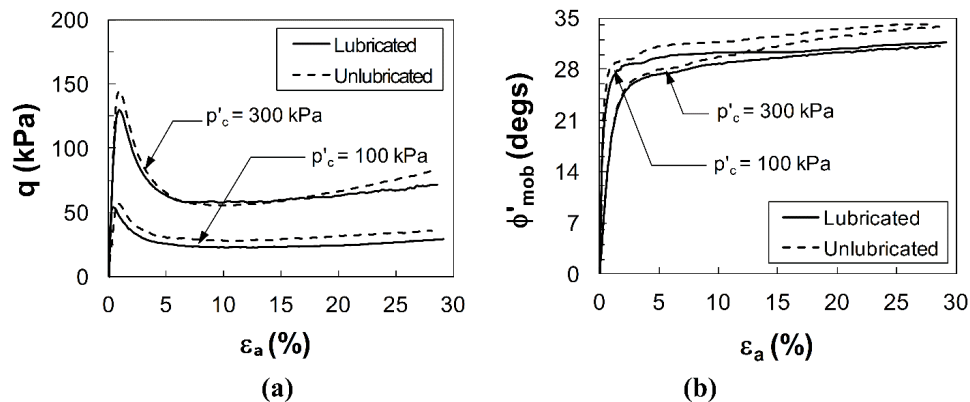


Figure 2: Effect of lubricated end platens on (a) undrained deviator stress – axial strain, and (b) mobilized friction angle (ϕ'_{mob}) in triaxial compression tests on 50 mm specimens



3.4 Specimen Deformation during Shear and Area Correction

The axial stress is computed by dividing the axial force by the cross-sectional area of the specimen. Ideally, the cross-sectional area is calculated based on the assumption that the sample deforms as a right circular cylinder during shear. As it is necessary to shear sand samples to large axial strains for critical state testing, initially-cylindrical specimen deforms substantially during the test and may significantly bulge. This bulging deformation makes the calculation of the cross-sectional area difficult and results in errors in the calculated deviator stress and accordingly the critical strength of the sand. Therefore, it is necessary to consider an effective cross-sectional area that takes into account the bulged shape of the specimen with a proper deformation pattern. Several methods have been developed for calculating the effective cross sectional area (A_e) of a specimen during shear. The choice of the area correction method should be based on the observed deformation profile of the specimen during and after shear. In the cylindrical deformation correction method recommended by the ASTM standard testing method D4767 (2011), the specimen is assumed to deform as a right cylinder during shear (La Rochelle *et al.* 1988). The corrected area is calculated as $A_e = A_c (1 - \varepsilon_v)/(1 - \varepsilon_a)$ where A_c is specimen's cross-sectional area before shearing, and ε_v and ε_a are the volumetric and axial strains, respectively. At a more complex level, the specimen is assumed to deform as a parabola (similar to a barrel) and A_e is computed at the mid-height of the specimen as $A_e = A_c \left[-0.25 + \sqrt{(25 - 20\varepsilon_a - 5\varepsilon_a^2)/4(1 - \varepsilon_a)} \right]^2$. Zhang and Garga (1997) also developed a method to correct the cross-sectional area of triaxial specimens. They performed triaxial tests where the samples' diameters were physically measured with a caliper at different strain levels and the deformation profile of the specimen was determined in each test. They found that the maximum specimen diameter occurred at the mid-height of the specimen and the specimen diameter changes with height at different axial strains were parabolic. Therefore, they suggested using the average specimen diameter within the middle third portion of the sample ($D_{1/3}$) to calculate the deviator stress as:

$$[4] \quad D_{1/3} = D_{max} - \frac{1}{12} (D_{max} - D_c)$$

$$[5] \quad D_{max} = \frac{D_c}{4} \left[\left\{ 30 \frac{(1 - \varepsilon_v)}{(1 - \varepsilon_a)} \right\} - 5 \right]^{\frac{1}{2}} - 1$$

The used lubricated end platens in this study reduced but did not eliminate specimen bulging as the specimens exhibited a slightly parabolic shape at the end of the tests. Accordingly, the method developed by Zhang and Garga (1997) for a parabolic specimen deformation is adopted to account for the enlarged area of the specimen. Note that the area correction method recommended by the ASTM standard D4767 (2011) assumes that the specimen deforms as a right circular cylinder. A right cylindrical deformation would occur if the specimen ends were perfectly frictionless and this correction could be used to replicate stress-strain response of an ideal specimen with no boundary effects. Figure 3 compares the undrained stress-strain responses and mobilized friction angles (ϕ'_{mob}) of loose sand specimens obtained using these area correction methods at $p'_c = 100$ kPa.

Compared to the final deviator stress without any area correction, the cylindrical (ASTM D4767, 2011), and the parabolic (Zhang and Garga 1997) area correction methods have reduced the final deviator stresses by an average of 30% and 24%, respectively. The corresponding friction angles (ϕ'_{cs}) are also decreased by up to 7° and 5°. The differences in the amounts of deviator stress and ϕ'_{mob} reductions from the two area correction methods further supports that the lubricated platens reduced but did not completely eliminate end friction. As shown in Figure 3, these differences become significant at the end of the test and they can lead to the overestimation of drained (ϕ'_{cs}) and undrained ($s_u(critical)$) shear strengths if the actual deformation pattern of the specimen is not taken into account in selecting the appropriate method of area correction. This error would further increase if lubricated end platens were not employed.

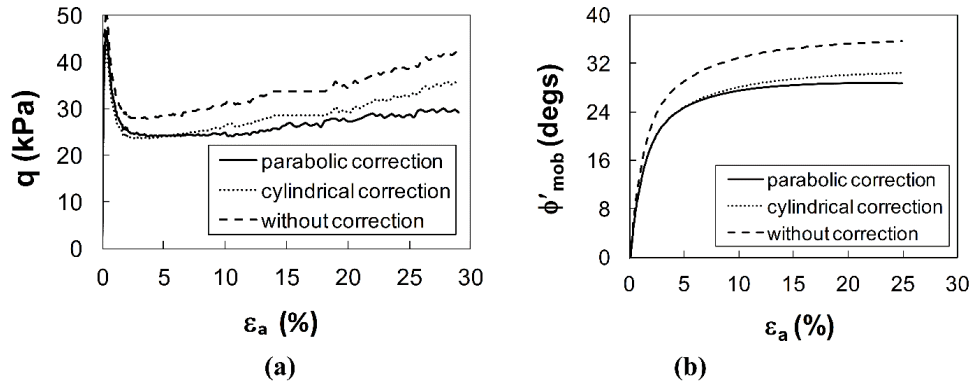


Figure 3: Effect of area correction on (a) undrained stress- strain response and (b) mobilized friction angle (ϕ'_{mob}) of loose sand in triaxial compression tests on 50 mm specimen diameters at $p'_c = 100$ kPa

3.5 Bedding Error

Although the use of lubricated latex sheets at the top and bottom of the specimens provided significant reduction in end restraint, they produced additional bedding errors with the application of the axial load as the latex sheets compressed and penetrated into the cavities among the sand particles. This error directly affected the precise measurement of ϵ_a . Sarsby *et al.* (1980) studied the compression of rubber layers in triaxial tests and the importance of correcting the measured axial displacement for the compression of latex sheets. They found that the bedding error was a logarithmic function of the effective axial stress, σ'_1 . Russell and Khalili (2004) subsequently conducted a series of one-dimensional compression tests on sands with and without lubricated latex layers and found that the compression of a single layer of rubber (Δ) was a logarithmic function of σ'_1 as shown in the following equation:

$$[6] \Delta(mm) = 0.0352 \ln \sigma'_1(kPa) - 0.0713$$

To improve the accuracy of axial displacement measurement during shear in the triaxial tests of this study, the bedding effect of 4 latex sheets (two on each end of a specimen) is accounted for by deducting their compression from the measured axial displacement. Eq. (6) is employed to estimate the amount of latex compression resulting from the axial stress applied on the specimen. Note that as the rubber membrane was already compressed following the consolidation stage, it was necessary to also include the amount of rubber compression produced by p'_c . The bedding error, if neglected, could greatly affect the measured ϵ_a and lead to significant underestimation of shear modulus from triaxial testing results. Our analysis indicated that the bedding error increased with increasing p'_c and it was larger in drained shear tests due to the steady increase of σ'_1 . The maximum bedding deformation in the experiments in this study was calculated as 0.38 mm, corresponding to about 5.1% of the measured total axial displacement.

3.6 Membrane Resistance

The rubber membrane used to seal a specimen in triaxial testing can carry a portion of the load applied on the specimen. This could be particularly significant in measuring the reduced s_u (critical) of loose soils after strain-softening and liquefaction. The ASTM standard method D7181 (2011) provides a correction for membrane resistance and recommends its application for when the effect of membrane resistance on deviator stress is greater than 5%. According to ASTM D7181 (2011), the shear stress carried by the membrane Δq_m (kPa) is calculated by the following equation:



$$[7] \Delta q = 4 \frac{E_m t_m \varepsilon_a}{D_c}$$

Where E_m (kPa) is the Young's modulus of the membrane material, t_m (mm) is the thickness of the membrane, and D_c (mm) is the specimen diameter after consolidation. Correction for membrane resistance was applied according to the ASTM standard method D7181 (2011) for all the experiments performed in this study. The Young's modulus of the latex membrane material was determined as 1,350 kPa from an extension test according to the ASTM D7181-11 standard procedure. Figure 4 shows the influence of membrane resistance on the stress-strain responses of 38 mm loose sand specimens at $p'_c = 100$ kPa. As shown in Figure 4, the contribution of membrane resistance increases with increasing axial strain and particularly at large strains where the reduced $s_u(\text{critical})$ is mobilized in a loose sand. Neglecting this correction could lead to an overestimation of up to 8% in the measured critical strength. For example, $s_u(\text{critical}) = 19.9$ kPa was measured in the 38 mm specimen at $p'_c = 100$ kPa, which includes the additional resistance of 3.0 kPa ($\approx 0.15s_u(\text{critical})$) provided by the membrane.

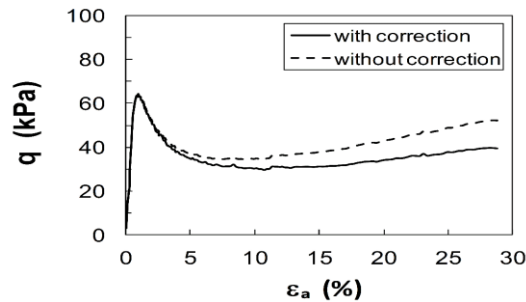


Figure 4: Effect of membrane resistance on the stress- strain responses of undrained triaxial compression tests on 38 mm diameter loose sand specimens at $p'_c = 100$ kPa

4 EFFECTS OF CORRECTIONS ON TRIAXIAL COMPRESSION TESTING RESULTS

The errors associated with triaxial testing and the correction techniques employed for each error were briefly reviewed above. Figure 5 demonstrates the relative effect of each correction on the effective stress paths and ϕ'_{cs} for the 50 mm specimens at $p'_c = 100$ kPa and 300 kPa. These plots clearly show the comparatively significant effect of area correction in reducing the mobilized deviator stress and ϕ'_{cs} .

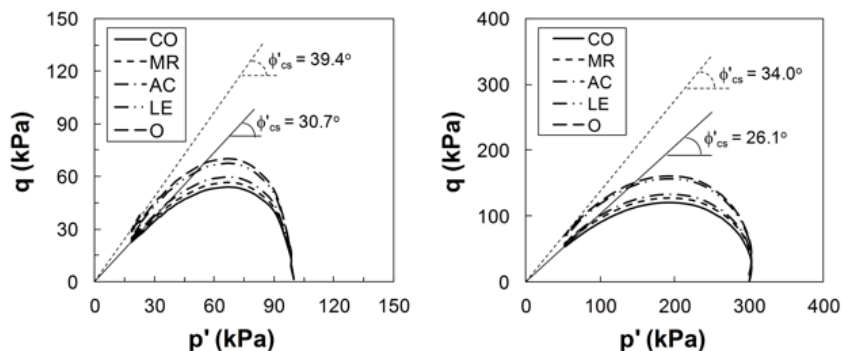


Figure 5: Effect of multiple corrections on effective stress paths and ϕ'_{cs} from the triaxial tests on 50 mm specimens at $p'_c = 100$ kPa & $p'_c = 300$ kPa (O: original data without corrections; LE: with lubricated platens; AC: with area correction; MR: with membrane resistance correction; CO: with all corrections)



In order to assess the significance of each error, identify how the corrections interact and compare the importance of the corrections, the aforementioned errors and the applied correction methods as well as the percentages of improvement of the associated parameter are summarized in Table 2 based on the triaxial tests of this study. The show that specimen bulging deformation is the most significant source of error affecting $s_u(\text{critical})$ and ϕ'_{cs} , followed by the effect of membrane resistance and end restraint. While bulging deformation and end restraint errors were largely corrected by the area correction and the using of enlarged and lubricated end platens in this study, specimen end restraints have an unsafe effect on triaxial test results by increasing soil shear strength and friction angle. According to Table 2, the studied parameters ($s_u(\text{critical})$, ϕ'_{cs} , e_{critical}) are affected by multiple sources of error, and $s_u(\text{critical})$, ϕ'_{cs} , and e_{critical} could be overestimated up to 44%, 14.7° and 0.7%, respectively if no any correction is applied. From the above analysis, correcting for the specimen cross-sectional area is the most significant correction for $s_u(\text{critical})$ and ϕ'_{cs} which needs to be adopted based on the observation of specimen shearing deformation. Accounting for these corrections is particularly necessary in critical state testing and liquefaction studies of loose sands and for the determination of the critical state line.

Table 2: Summary of the applied corrections and percentage improvements of triaxial test results on loose Ottawa sand

| Correction | Parameter | Mechanism | Adjustment |
|---------------------|------------------------|----------------------|------------------------|
| Enlarged platens | $s_u(\text{critical})$ | End restraints | -10% (- 8 to -12) |
| | ϕ'_{cs} | | -3.6° (-3.1° to -4.2°) |
| Area correction | $s_u(\text{critical})$ | Specimen bulging | -24.5% (-20 to -29) |
| | ϕ'_{cs} | | -8.9° (-7.8° to -10°) |
| Membrane resistance | $s_u(\text{critical})$ | Membrane resistance | -11% (-8 to -15) |
| | ϕ'_{cs} | | -3.1° (-2.6° to -3.6°) |
| Volume change | $s_u(\text{critical})$ | Saturation | 1.5% (2.0 to 3.0) |
| | ϕ'_{cs} | | 0.9° (0.8 to 1.0) |
| | e_{critical} | | -1.1% (-0.9 to -1.3) |
| Bedding error | e_{critical} | Membrane penetration | 0.36% (0.32 to 0.40) |
| | ϵ_a | Latex compression | -2.5% (-0.5 to -5.5) |

5 CONCLUSION

The experimental errors affecting the triaxial shearing behavior of loose sand have been thoroughly reviewed in this study, which illustrated the significant effects of end restraint and triaxial data corrections on sand shearing behavior. Non-uniform deformations at large strains (which is often required to achieve a critical state), significantly affect the strength of sands. It was demonstrated that lubricated and enlarged end platens are helpful methods to minimize the effects of end restraint and promote uniform deformations during shear. As a result of these improvements, accurate volume change in drained shear tests as well as lower deviator stresses and higher pore pressures were measured in the undrained shear tests. It was found that non-lubricated end platens could result in an average of 10% overestimation of $s_u(\text{critical})$. While lubrication improved the uniformity of the specimens' deformation, it did not completely eliminate non-uniform deformations and the final specimen shapes were slightly parabolic and thus an area correction conforming to the shape of the deformed specimens was applied to account for this barreling deformation of the specimen and correct the calculated axial stress. Accordingly, the critical strength was further reduced by an average of 24.5%. The bedding error due to the compression of the latex membrane used in the enlarged platens technique increased the measured axial strain by an average of 2.5%. It was further observed that neglecting membrane resistance could lead to the



overestimation of sand strength up to an average of 11%. An important factor affecting the behavior of sands is its void ratio. The volume change during back pressure saturation and due to membrane penetration could affect the determination of soil void ratio. The results of volume change analyses of this study indicated that ignoring the volume change during saturation could lead to an overestimation of the specimen's void ratio up to 0.01 which corresponds to about 3% in terms of relative density. It was found that area correction was the most significant source of error observed in this comprehensive study which requires appropriate correction for triaxial shear testing of loose sands.

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