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The Undrained Cyclic Response of Monterey Sand in Direct Simple Shear

C. Cappellaro[1] and M. Cubrinovski[2]

[1]PhD Student, Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand PH (64) 3-3642987; email: claudio.cappellaro@pg.canterbury.ac.nz
[2]Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand PH (64) 3-3642251; email: misko.cubrinovski@canterbury.ac.nz

ABSTRACT

The high impact that earthquake-induced liquefaction has on the New Zealand economy, as observed during the 2010-2011 Canterbury Earthquake Sequence in the Christchurch urban area, requires a better understanding of the undrained response of silty sands to cyclic shear loadings. This problem remains still difficult to address because progresses are hindered by the paucity of laboratory experimental data regarding silty sands. In order to address this issue, a series of triaxial tests have been performed at the University of Canterbury since 2011 on undisturbed samples recovered from seven sites in Christchurch. This study aims at using a direct simple shear device for improved evaluation of earthquake and liquefaction response of silty soils. In the first phase of the experimental programme, comprehensive calibration of the testing device and testing procedures has been performed. This paper summarizes key aspects of this important preparatory phase of the testing including description of testing procedures. Reliability of testing procedures and obtained results are assessed by means of a series of simple shear tests performed on a clean sand, whose results are compared against data from the literature.

Keywords: liquefaction, direct simple shear, cyclic, undrained, Monterey sand

1 INTRODUCTION

1.1 Recent studies on soils from Christchurch

Earthquake-induced liquefaction damage is one the principal seismic hazards in New Zealand, and it is responsible for significant socio-economic costs. For instance, soil liquefaction can be accounted for approximately 50% of the NZ$ 40 billion losses caused by the 2010-2011 Canterbury Earthquakes, in which severe damage to roads and bridges, residential houses, commercial buildings, lifeline facilities and levees was widely observed (Cubrinovski et al., 2014).

Early studies on soil liquefaction essentially focused on loose clean sands (i.e. sands with less than 5% particles smaller than 75 μm), as the first well-documented case histories reported liquefaction in this type of soils (Seed, 1979). Recent experience suggests that liquefaction, lateral spreading and flow failure involve sands with fines (Cubrinovski and Ishihara, 2000). Within this list of recent evidence is also the urban area of Christchurch, where liquefaction-related phenomena have been observed in sandy silts deposits of fluvial origin (Bray et al., 2015; Cubrinovski and Robinson, 2015). This implies the need to establish a reliable basis for liquefaction evaluations of silty sands (fines-containing sands) rather than always referring to idealized clean sands.

Fabric, i.e. the arrangement of soil grains in the packing (skeleton), and structural features such as soil layering are the product of processes leading to the formation of natural soil deposits, and are unique to the depositional environment. The liquefaction strength of cohesionless soils has been shown to be strongly influenced by fabric (Ladd, 1977; Mulilis et al., 1977) and layered structure (Verdugo et al., 1995). In order to capture these effects, ideally one should test undisturbed specimens collected from the field. However, sampling of cohesionless soils without significant disturbance is a difficult and expensive task. This is the main reason why research in the past has often made use of reconstituted specimens prepared in the laboratory. Obviously, in order to get a better picture of the liquefaction behaviour of natural soil deposits, one has to reproduce in the lab a fabric similar to that encountered in the field. There exist several specimen reconstitution techniques, each one of them resulting in a different fabric. Among them, moist tamping has been widely used by researchers as it allows to easily prepare either loose or dense specimens (Ishihara, 1993). Fabric obtained with moist tamping, however, is not representative of fabric of natural soils. Although it is more difficult to employ than moist tamping, the water sedimentation technique is considered to result in a fabric more closely resembling that of fluvial soil deposits (Vaid and Sivathayalan, 2000).

Previous research performed at the University of Canterbury includes investigations of different aspects of the undrained cyclic and monotonic triaxial response of fines-containing sandy soils from Christchurch, and also undisturbed specimens have been used to account for the effects of natural fabric. Rees (2010) focused on moist-tamped specimens with various fines contents, while Taylor (2015) presented comparisons between undisturbed and moist-tamped specimens of another set of Christchurch soils. Additional advanced laboratory testing of undisturbed specimens from two different sites are presented by Stringer et al. (2015) and Beyzaei et al. (2015).

This study represents a continuation of these efforts, as it aims to assess how fabric and layered structure influence the undrained cyclic response of sandy soils from Christchurch in direct simple shear (DSS) conditions. This will be achieved by performing comparative tests on undisturbed specimens, collected with the Gel-Push and Dames & Moore samplers, and on water sedimented specimens of the same soils prepared in the laboratory. This experimental series is preceded by calibration and verification tests on moist-tamped specimens of Monterey #0/30 sand presented in this paper. As this material has been extensively employed in past laboratory studies on liquefaction, it provides a good benchmark in the development of testing protocols for subsequent investigations on Christchurch natural soils.

1.2 Features of cyclic DSS for liquefaction studies

Past laboratory studies on the undrained cyclic behaviour of cohesionless soils have made extensive use of the triaxial device because of its common availability in research facilities and of its relative simplicity in use. Nevertheless, as level-ground free-field response involves simple shear mode of deformation, the DSS test is capable of reproducing the field conditions of deformation more rigorously. The conversion of triaxial test data to simple shear mode of deformation, as encountered in level-ground free-field conditions, has traditionally been described in terms of cyclic stress ratio (CSR) using Equation 1:

$$CSR = [\tau / \sigma'_v]_{field} = (1 + 2K_0) / 3 \cdot [|\sigma_a| / (2 \cdot \sigma'_c)]_{TX} \qquad (1)$$

where the stress terms are defined in Figure 1. Stress induced in triaxial testing are very different from stresses imposed by earthquakes to soils in level-ground free-field deposits. The actual relationship between liquefaction resistance in triaxial and simple shear conditions is a complex function depending on the tested soil, amplitude of imposed cyclic stresses, and soil fabric, among others, and these aspects are not captured by Equation 1 (Tatsuoka et al., 1986). Direct simple shear (DSS) testing was conceived as a means to overcome this shortcoming of triaxial testing. Ideal undrained DSS loading conditions correspond to a planar state of strain: a soil element undergoes shear strains in the vertical plane while subjected to shear stresses in the horizontal plane; constant height, volume and total vertical load are enforced during the shearing.

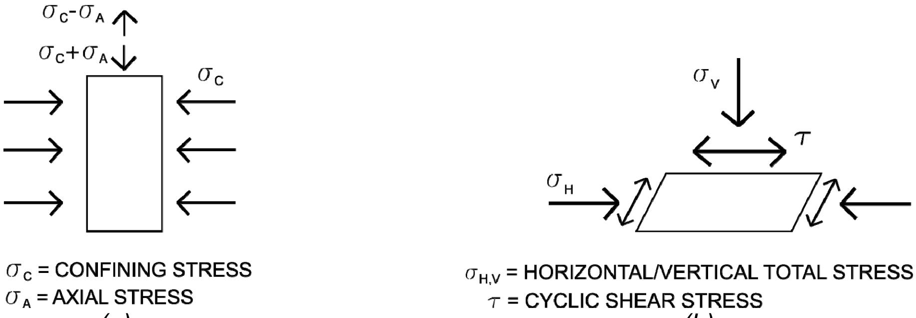
Over the years, different procedures and designs of testing apparatuses have been developed in order to overcome several technical difficulties in achieving DSS conditions in the practice, as explained by Boulanger (1990) and Kammerer (2002). Tested specimens can have rectangular or circular cross-section. The states of stress and strain across the specimen are highly non-uniform, especially for specimens with circular cross-section. This induces rocking in the loading system, which represented a major issue for early DSS devices (e.g. Ishihara and Yamazaki, 1980). Also, in order to overcome potential scale effects, tested specimens should have a large diameter-to-height ratio (≥ 4), as opposed to triaxial specimens. Lateral confinement to the specimen can be provided in different ways, for example by means of a wire-reinforced membrane (NGI-type devices), by a stack of rigid rings (SGI-type devices), or by applying a lateral pressure to a specimen surrounded by a plain latex membrane, similarly to a triaxial test.

This experimental study makes use of a custom-designed DSS device built at the University of California, Berkeley (refer Figure 2). Tested specimens are cylindrical in shape, 61 mm in diameter and 15 mm in height, and laterally confined by a plain latex membrane. The device is provided with a pressure chamber, where compressed air is used to apply confining stresses to the specimen, and makes use of back pressure for saturation. The upper and lower faces of the specimen are in contact with two porous stones fitted in the recesses of two aluminium caps. These provide a means to realize a firm connection between the specimen and the horizontal and vertical loading systems. The bottom cap is clamped to a sliding table mounted on track bearings and connected to a servo-controlled pneumatic actuator. The top cap is connected, via an analogous sliding block on track bearings, to a manually-controlled pneumatic actuator. The systems of track bearings are designed to minimize rocking of the top cap and friction. An array of transducers is employed to measure and record vertical and horizontal loads and displacements, pore water pressures, and volume changes.

2 EXPERIMENTAL SETUP

2.1 Test material

The test material used in this study is Monterey #0/30 sand, a clean, uniform, medium grain-sized sand with sub-rounded particles from Monterey, California. Several studies on the undrained cyclic behaviour of coarse-grained soils made use of either Monterey #0 or #0/30 sands, which differ for the method used to separate the extracted material based on grain size (Kammerer, 2002). The two sands, however, are very similar to each other (Wu, 2002), and references describing tests on either one or the other material represent a good reference for comparison with this study. Relevant index properties for Monterey sand are listed in Table 1. Minimum and maximum dry densities for the present study were determined according to the Standard for soil testing of the Japanese Geotechnical Society (JGS 0161-2009). Particle size distribution was determined from five different samples of oven-dried material using the laser diffraction method (ASTM C1070-0).



(a) *(b)*

Figure 1. Triaxial (left) and idealized simple shear (right) cyclic loading conditions.

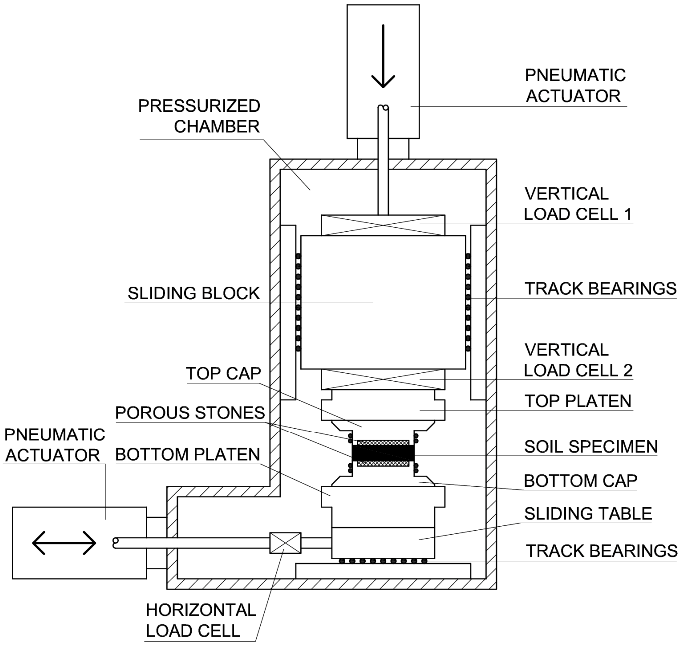


Figure 2. Schematic diagram of DSS device used in this study (modified, after Boulanger, 1990).

Table 1. Index properties of Monterey #0 and #0/30 sand.

Type of sand	G_s	e_{min}	e_{max}	D_{50} [mm]
Monterey #0 Sand (Silver et al., 1976)	2.65	0.56	0.85	0.36
Monterey #0/30 Sand (This study)	2.64	0.585	0.837	0.59

2.2 Testing programme and procedure

This paper reports test results from five cyclic DSS tests performed on moist-tamped Monterey #0/30 sand specimens. Testing on a clean sand is deemed to provide a useful basis to validate testing procedures and assess capabilities of testing equipment before further testing is carried out on soils from Christchurch. This is ensured first by evaluating consistency and repeatability of test results within this experimental series, while test results from literature studies performed in similar conditions provide an additional and independent basis for comparison and results evaluation.

Specimens were prepared by the moist tamping technique (Ishihara, 1993). Moist sand, mixed at 8% water content, is tamped in a single layer using a tamping rod. The top cap is then placed on top of the specimen, and a vacuum of 30 kPa is applied.

Carbon dioxide is percolated through the specimen for 90 minutes, followed by percolation of de-aired water, in order to improve subsequent saturation. Back pressure is increased to 50 kPa before the vertical effective stress is increased to σ'_v = 60 kPa, with σ'_h / σ'_v = 0.5. A subsequent increase of σ'_v to 100 kPa takes place at the same (constant) σ'_h / σ'_v ratio. This consolidation ratio corresponds to average K_0 conditions across a specimen for Monterey sand (Riemer, 1992). Back pressure is finally raised to 250 kPa while keeping the effective stress constant. For these tests, pre-shearing B-values ranged between 0.91 and 0.94, which indicate nearly fully saturated soil. Height and volume changes were monitored during all these preparation stages, and were found to be very small for this material.

Before shearing, the vertical piston is clamped in position to enforce a constant height condition, and undrained conditions are then imposed. A sinusoidal cyclic shear load of pre-determined amplitude is applied by the servo-control system at a frequency of 0.05 Hz. The cyclic shearing phase takes place at constant total horizontal stress, σ_h.

Although the target dry density was 1.57 g/cm^3 (D_R = 62%), initial densities of specimens ranged between 1.55 and 1.60 g/cm^3 (D_R = 54-73%). Both the small size of the specimen and the relatively narrow range of limiting void ratios of Monterey sand (which is used in computations of relative density) contributed to the dispersion in the initial relative density. Use of larger specimens would have certainly minimized this effect. However, future planned tests on Christchurch soils will be constrained by the diameters, respectively 70 mm and 61 mm (Beyzaei et al., 2015) for the Gel-Push and Dames & Moore samplers, using 61 mm specimens for testing after careful trimming the soil. For this reason, testing of larger reconstituted specimens of clean sand was not a priority in this study.

3 ANALYSIS OF EXPERIMENTAL RESULTS

Figure 3 shows typical time histories of shear stress, shear strain and excess pore water pressure for a DSS test. Figure 4 plots the experimental results in terms of number of cycles necessary to develop 10% double amplitude (DA, i.e. peak-to-peak) axial strain (triaxial tests) or 15% DA shear strain (DSS tests) against imposed CSR. Specimens subjected to higher CSR reach a condition of initial liquefaction in a smaller number of cycles, demonstrating internal consistency for this test series. These results can be compared with those performed at 60% relative density by Tatsuoka et al. (1980), who employed an experimental setup analogous to that of this study. The good agreement between the two DSS datasets is encouraging, as it confirms the quality of test results obtained by this study.

On the same plot are shown also cyclic triaxial data for Monterey Sand at 60% relative density (Markham, unpublished data; Silver et al., 1976). The tests by Markham were performed at UC Berkeley with the same batch of Monterey #0/30 sand employed in this study. The test results from Markham and Silver et al. (1976) suggest that no discernible difference can be inferred between the cyclic liquefaction strength of Monterey #0 and #0/30 sands. Comparison between triaxial and DSS test results also provides further evidence of the absence of significant difference in the liquefaction resistance between these two test conditions.

4 CONCLUSIONS

A series of cyclic DSS tests on moist-tamped specimens of Monterey #0/30 sand was performed for comprehensive calibration of the testing device and testing procedures developed as part of a study on the liquefaction behaviour of Christchurch natural soils. Mutual consistency among test results, and good agreement with data from the literature for the same soil support validity and reliability of adopted testing procedures. Before effective testing of fines-containing soils from Christchurch is undertaken, testing of Monterey sand will be extended to water sedimented specimens, so as to establish a rigorous protocol for preparation and testing of also this type of specimens.

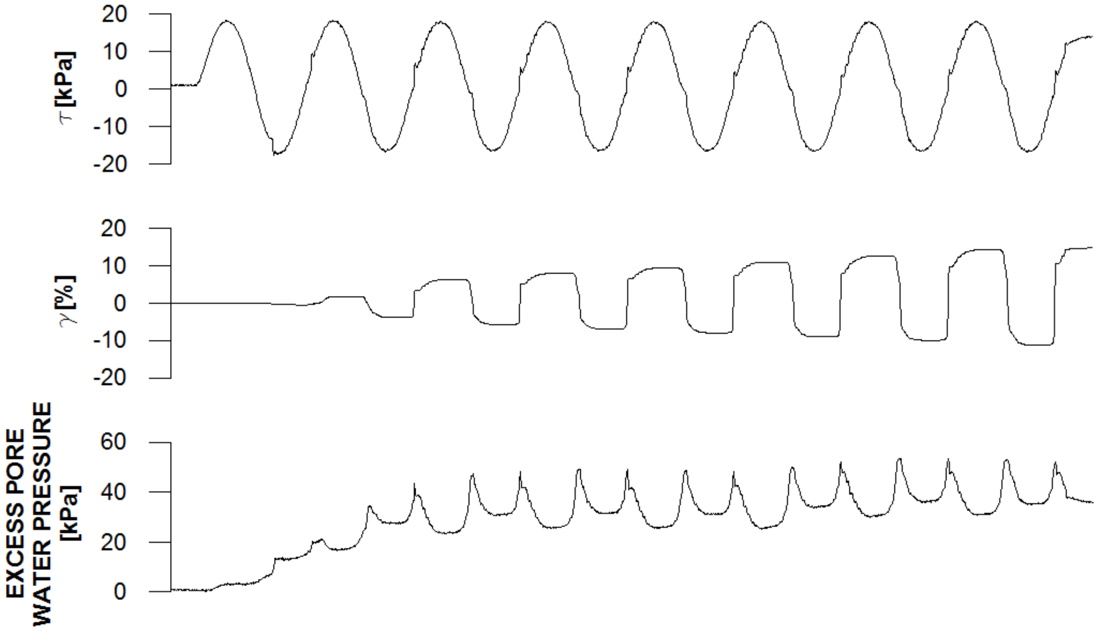
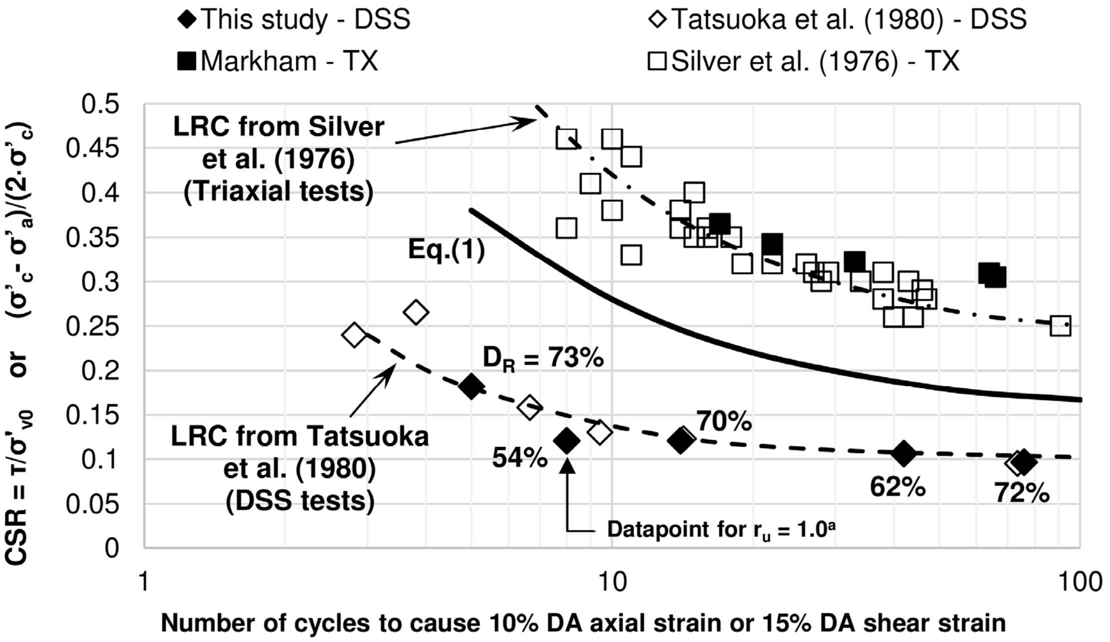


Figure 3. Typical time histories of shear stress, shear strain, and excess pore water pressure for DSS test (Test MTS_SM16, D_R = 73%, CSR = 0.18).



[a] Sudden loss of stiffness at the attainment of r_u = 1.0 (i.e. state of zero effective stress) prevented recording of any additional shear strains.

Figure 4. Liquefaction Resistance Curves of moist tamped Monterey #0/30 (filled points) and #0 (empty points) sand at 60% relative density from DSS and triaxial tests.

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