

## Undrained cyclic direct simple shear testing of Christchurch sandy soils

C Cappellaro, M Cubrinovski, G Chiaro, M E Stringer  
Department of Civil and Natural Resources Engineering, University of Canterbury, NZ  
[claudio.cappellaro@pg.canterbury.ac.nz](mailto:claudio.cappellaro@pg.canterbury.ac.nz) (Corresponding author)

J D Bray, M F Riemer  
Department of Civil and Environmental Engineering, University of California, Berkeley, US

Keywords: liquefaction, cyclic direct simple shear, water sedimentation, sandy soil.

### ABSTRACT

The earthquakes that hit the region of Canterbury, New Zealand, in 2010-2011 resulted in severe damage to buildings and infrastructure due to widespread liquefaction of natural clean sand and silty sand deposits of fluvial origin. Despite the significant hazard posed by earthquake-induced liquefaction to New Zealand communities and economy, the undrained cyclic behaviour of silty sands remains poorly understood, with few laboratory data available to support developments in research and design methodologies.

For these reasons, a comprehensive laboratory testing programme on Christchurch soils has been undertaken at the University of Canterbury since 2006. After the 2010-2011 Canterbury Earthquake Sequence, these research efforts have been extended to include both broad field and experimental investigations, in collaboration with the University of California, Berkeley. Within this context, this paper describes the preliminary results from a series of undrained cyclic Direct Simple Shear (DSS) tests performed on specimens prepared with a natural clean sand retrieved from Christchurch, as part of a broader testing programme which will be extended to include also silty sands and stratified silt-sand specimens. Test specimens are reconstituted with the water sedimentation method. In comparison to other deposition methods, this technique allows the preparation of specimens with soil fabric and soil structural features, such as segregation and layering, which are more representative of the characteristics of natural fluvial deposits like those typically encountered in Christchurch. Analysis of experimental data provides the first evidence on how the DSS response of these soils is affected by the magnitude of the imposed cyclic loading and by soil density.

## 1 INTRODUCTION

### 1.1 Current research context on the liquefaction behaviour of sandy soils

Earthquake-triggered soil liquefaction is the temporary reduction in soil strength and stiffness accompanying the build-up of excess pore water pressures induced by seismic stress waves propagating through the ground. Early studies on soil liquefaction essentially focused on loose clean sands (i.e. sands with less than 5% fines or particles smaller than 75  $\mu\text{m}$ ), as the first well-documented case histories reported liquefaction in this type of soils (Seed, 1979). Later evidence, however, added a significant number of case histories of liquefaction, lateral spreading and flow failure in fines-containing soils (Cubrinovski & Ishihara, 2000), including the phenomena observed within the urban area of Christchurch in 2010-2011 (Cubrinovski et al., 2011). This leads to the necessity to establish a reliable basis for liquefaction evaluations of silty 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 (micro- and macro-structure) are the outcome of the formation processes 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 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 produce in the laboratory 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. Fabric obtained with moist tamping, however, is not representative of the 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 & Sivathayalan, 2000).

Previous research performed at the University of Canterbury includes undrained cyclic and monotonic triaxial tests of fines-containing sandy soils from Christchurch. Rees (2010) focused on specimens with various fines contents reconstituted by moist tamping, while Taylor (2015) presented comparisons between undisturbed and moist-tamped reconstituted specimens for another set of Christchurch soils. Additional data on undisturbed specimens of Christchurch soils are presented by Stringer et al. (2015) and Beyzaei et al. (2015).

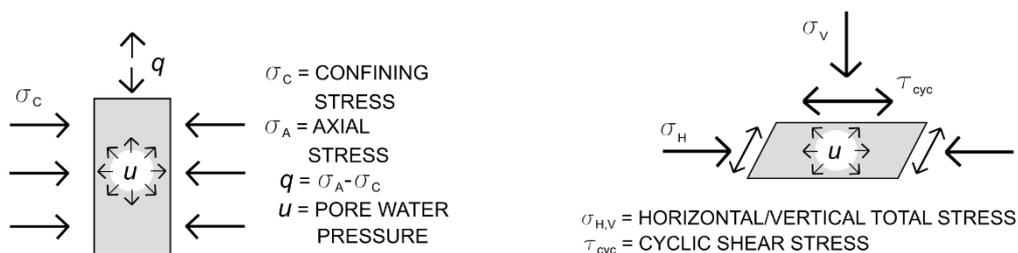
This study is a continuation of these efforts. Its aim is to highlight how fabric and layered structure influence the undrained cyclic response of sandy soils from Christchurch in Direct Simple Shear (DSS) conditions. This will be achieved by performing comparative tests on undisturbed specimens, collected with the Gel-Push and Dames & Moore samplers, and on specimens of the same soils prepared in the laboratory using the technique of water sedimentation. In this paper, experimental results for DSS tests on specimens of a clean sand sourced from Christchurch reconstituted at different relative densities are presented. Given the extensive research performed in the past on the undrained cyclic response of clean sands, this test series represents the most relevant reference benchmark for the analysis of subsequent tests on fines-containing sands.

## **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 relative simplicity in use and its more common availability in research facilities compared to other testing apparatuses. However, level-ground free-field response induced by earthquake shaking involves a simple shear mode of deformation which is reproduced more rigorously in a Direct Simple Shear test. The conversion of triaxial test data to simple shear mode of deformation, as encountered in level-ground free-field conditions, has traditionally been expressed in terms of the cyclic stress ratio (CSR) using equation (1):

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

where the effective stresses terms herein employed are consistent with the total stresses shown in Figure 1. The actual relationship for the liquefaction resistances between triaxial and simple shear conditions is a complex function depending on factors such as tested soil, amplitude of imposed cyclic stresses, and soil fabric, among others, which are not captured by equation (1) (Tatsuoka et al., 1986). One of the main reasons for this discrepancy is that the stresses imposed on a triaxial test specimen are very different from the stresses induced by earthquakes to soils in level-ground free-field deposits. DSS testing was conceived as a means to overcome this shortcoming of triaxial testing.



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

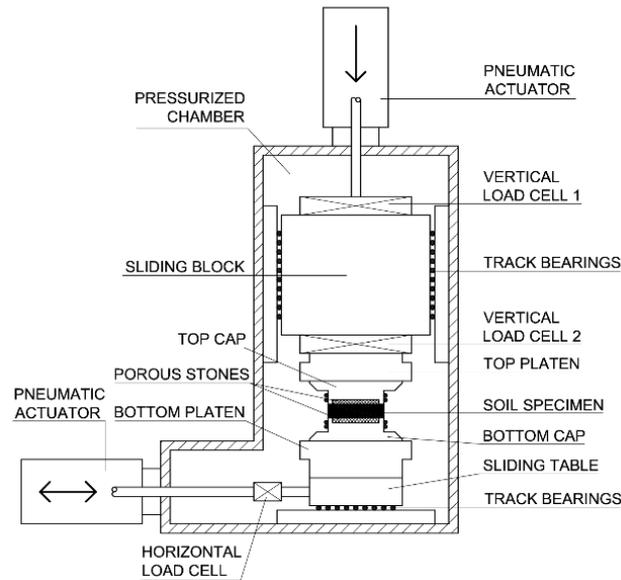
Ideal undrained DSS loading conditions correspond to a planar state of strain: a soil element undergoes shear strains in the vertical plane while subjected to shear stresses in the horizontal plane; constant height and constant volume are enforced during the shearing process. Implementation of the simple shear conditions in the practice presents several technical difficulties (see for example Boulanger, 1990). This has resulted, over the years, in the development of a variety of testing procedures and designs of testing apparatuses. Tested specimens can have rectangular or circular cross-section. Circular specimens can be laterally confined by means of a wire-reinforced membrane (NGI-type devices), by a stack of rigid rings (SGI-type devices), or by wrapping the specimen within a plain latex membrane and applying a lateral pressure, analogously to a triaxial test. The design of the loading system must minimize rocking of the horizontal faces of the specimen, which stems from the significant non-uniformity in the states of stress and strain across the specimen. Also, in order to overcome potential scale effects, tested specimens should have a large diameter-to-height ratio ( $\geq 4$ ), as opposed to triaxial specimens. This may result in a specimen with a relatively small height, which in turn may pose difficulties in accurately estimating the relative density of the specimen, an issue that has been encountered in this study.

This experimental study makes use of a custom-designed DSS device built at the University of California, Berkeley (Figure 2). Tested specimens are cylindrical in shape, 61 mm in diameter and 15 mm in height, and wrapped within 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 a 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. A set of transducers is employed to measure and record vertical and horizontal loads and displacements, pore water pressure, and volume change.

## 2 EXPERIMENTAL SETUP

### 2.1 Test material

The tests presented in this paper were performed on a sand retrieved from a site in the Red Zone of Christchurch. Relevant index properties for this sand are listed in Figure 3. As the amount of soil available to prepare reconstituted specimens was limited, the same batch of soil had to be reused multiple times in the testing. In order to assess the amount of fine particles lost during the water sedimentation process and testing procedures, grain size analyses were performed at the beginning of this DSS testing series, and every time all the soil available from this batch had been used for preparing a specimen. Each repetition comprised a dry sieve analysis, carried out on two samples, and a Laser Diffraction Analysis performed on four samples.



**Figure 2: Schematic plot of the DSS device (modified, after Boulanger, 1990)**

Figure 3 shows the particle size distribution curves obtained from the Laser Diffraction Analysis. Although the water sedimentation process seems to result in some changes in the particle size distribution with respect to the original soil, the magnitude of these alterations can be treated as negligible for the purposes of the present study.

## 2.2 Testing procedure

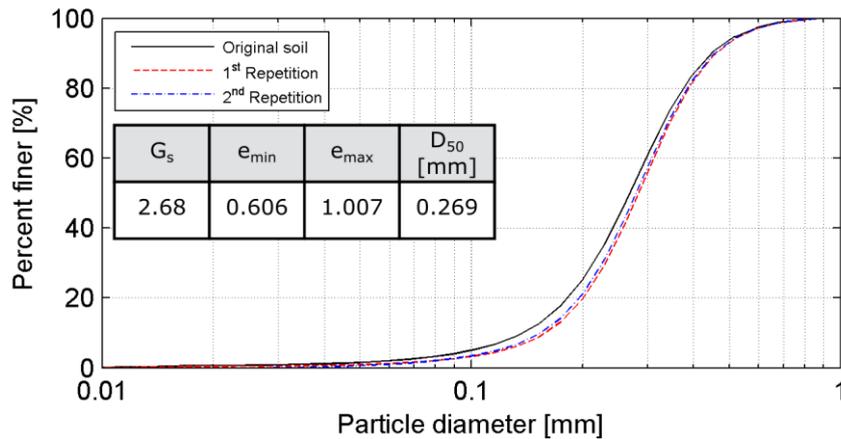
Test specimens were prepared using the water sedimentation technique. With this method, dry soil was poured (using a funnel and a rubber hose) into a mould filled with water, yielding a specimen in a loose state. In this study, the typical relative density for the sand obtained by this procedure was about 50%. The top surface of the specimen was then levelled with a spatula, and the top cap was carefully positioned on it. For the preparation of denser specimens, subsequent densification was achieved by positioning additional weights on the top cap and using a mallet to impose small vibrations for a pre-determined amount of time to the table on which the mould was resting. By varying the mass of the weights and the duration of the vibration process, target relative densities of about 60% and 70% were achieved. A vacuum of 25 kPa was then applied to the specimen.

Saturation was performed by first percolating carbon dioxide through the specimen for at least 30 minutes, followed by percolation of de-aired water, and finally by pressurizing the pore water in the specimen to at least 200 kPa. Post-consolidation B-values ranged between 0.92 and 0.97.

Specimens were consolidated anisotropically to  $\sigma'_v = 100$  kPa, with a ratio  $K = \sigma'_h/\sigma'_v = 0.5$ . Imposing this stress ratio gives an approximate condition of one-dimensional consolidation, as was verified by the negligible average consolidation radial strains.

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

$$\sigma_h = \sigma_{\text{cell pressure}}$$



**Figure 3: Index properties and particle size distribution curves from Laser Diffraction Analysis for test sand**

### 3 PRESENTATION AND DISCUSSION OF TEST RESULTS

Figure 4 shows results from three cyclic DSS tests run at similar levels of cyclic shear stress on specimens prepared at the three target relative densities. Plotted on the left are the effective stress paths in the  $\tau$ - $\sigma'_v$  space, while on the right is portrayed the shear stress-shear strain response of the specimens, which exhibits the typical hysteresis loops. The repeated shearing actions imposed on the specimens generate excess pore water pressure which results in a decrease in the vertical effective stress,  $\sigma'_v$ . This is accompanied by a loss of stiffness which in turn leads to a progressive development of shear strains. A characteristic feature of the hysteresis loops of the DSS tests herein described is their symmetric shape, unlike those obtained from cyclic triaxial tests (see for example Rees, 2010, and Taylor, 2015).

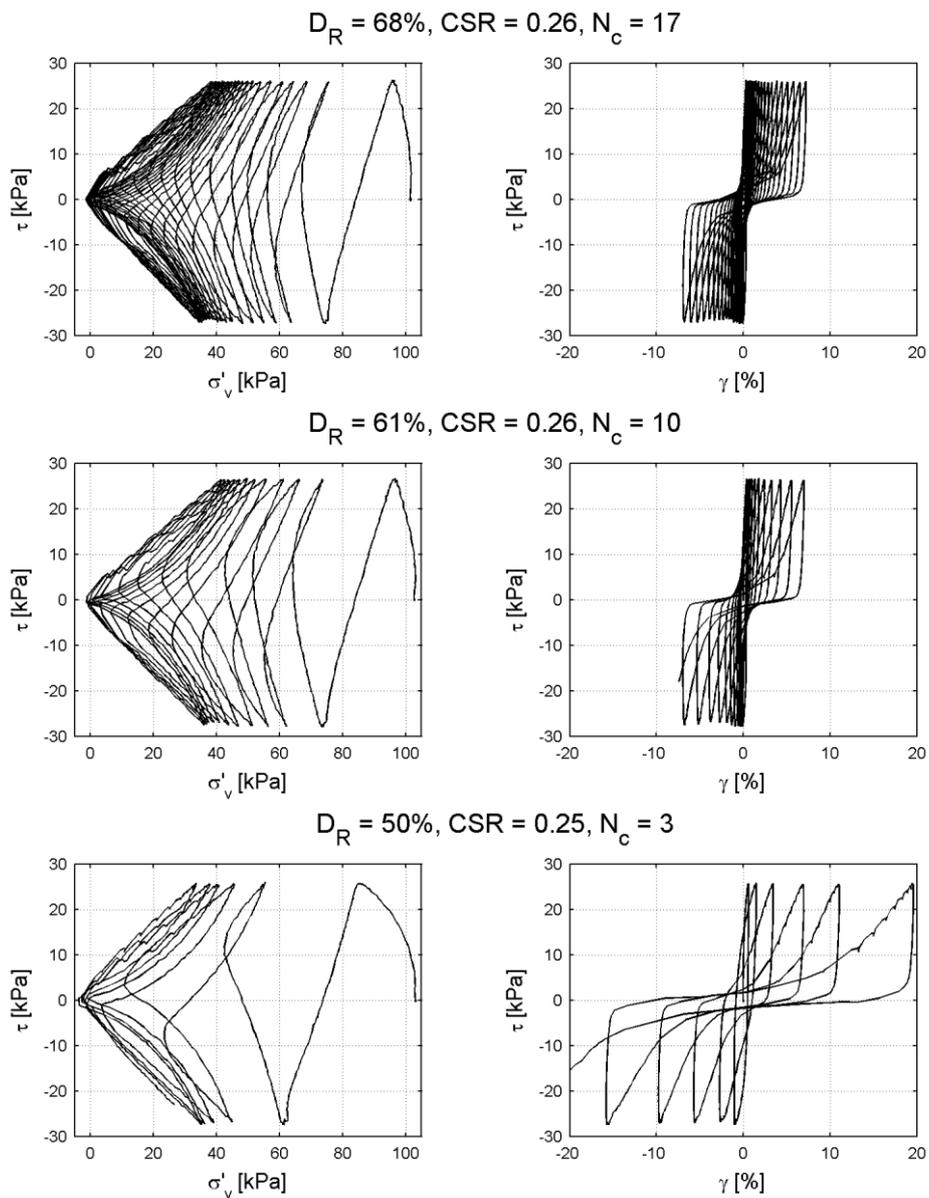
The three specimens exhibit a different response to cyclic loading depending on their relative density: the looser the specimen, the higher its tendency to contract is, which under undrained conditions means that higher pressures are generated during each loading cycle in the pore water. Thus, a loose specimen liquefies more rapidly than a dense specimen, producing very large strains in a small number of loading cycles. This is a well-established pattern for the behaviour of clean sands. Figure 4 shows that under  $CSR = 0.25$ - $0.26$ , the number of cycles required to produce a double amplitude shear strain of 7.5% was  $N_c = 3, 10$  and 17 cycles for the specimens with relative densities at  $D_R = 50\%$ , 61% and 68%, respectively.

Figure 5 summarizes the experimental results from all tests performed so far in terms of number of cycles necessary to develop 7.5% double amplitude (DA, i.e. peak-to-peak) shear strain against imposed CSR. The effect of relative density on the liquefaction resistance is evident in the figure, where higher CSR values are needed to produce liquefaction at a given number of cycles for denser specimens. Fifteen DSS tests have been performed so far, but the experimental testing is still ongoing. An additional small number of tests on the same material is required to obtain a sufficient number of data points for each density bin between 1-3 and 30-50 cycles to liquefaction, as this is the range of interest for most of the earthquake geotechnical engineering applications.

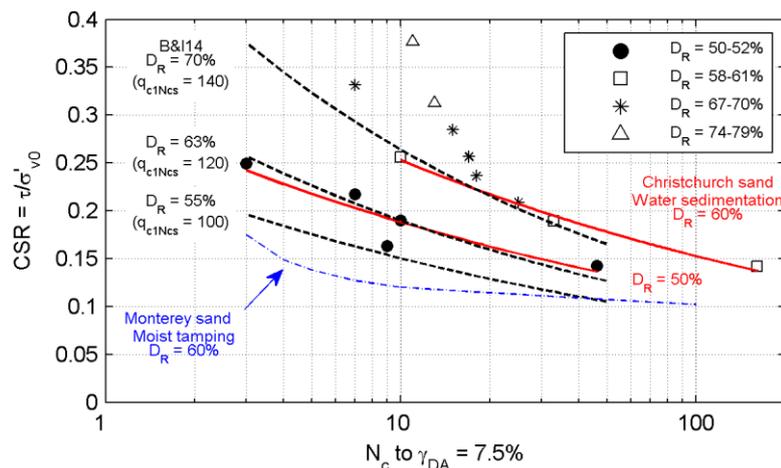
Plotted in Figure 5 are the experimental Liquefaction Resistance Curves for Christchurch sand at relative densities of 50% and 60%, and for Monterey #0/30 sand specimens prepared by moist tamping at 60% relative density (Cappellaro & Cubrinovski, 2016). This curve represents a useful reference because several studies on the undrained behaviour of coarse-grained soils described in the literature employed Monterey sand as test material. The Liquefaction Resistance Curves defined in accordance with Boulanger & Idriss (2014) for values  $q_{c1Ncs} = 100, 120$  and 140 of the

normalized cone tip resistance in clean sand are also shown for comparison. The  $q_{c1Ncs}$ -based curves are the standard tool for the ordinary assessment of liquefaction hazard, and are derived from the boundary between liquefaction-no liquefaction case histories recorded at different sites during past earthquakes. In this sense, they represent a lower limit to the resistance to liquefaction of sands. The procedure to compute the  $q_{c1Ncs}$ -based curves plotted in Figure 5 is detailed in Cubrinovski et al. (2017);  $q_{c1Ncs}$  values have been converted to equivalent relative densities  $D_R$  using the relationship indicated by Idriss & Boulanger (2008).

Figure 5 shows that the liquefaction resistance recorded in the DSS tests for water sedimented Christchurch sand specimens (red curves) is higher than the  $q_{c1Ncs}$ -based resistance (dashed lines) for similar values of relative density. This difference can be ascribed to the conservativeness in the definition of the liquefaction-no liquefaction boundary from which the  $q_{c1Ncs}$ -based strengths are derived. On the other hand, Monterey sand exhibited a significantly lower liquefaction resistance, possibly because the fabric attained by this sand when moist tamped is particularly unstable in comparison to fabrics encountered in natural soil deposits.



**Figure 4: Stress paths and stress-strain curves for cyclic DSS tests on specimens of Christchurch sand prepared by water sedimentation at different relative densities**



**Figure 5: Number of cycles against CSR for 7.5% DA shear strain in DSS for Christchurch sand (red lines) and Monterey #0/30 sand (blue line), and from  $q_{c1Ncs}$  relationships by Boulanger & Idriss (2014) (dashed black lines)**

The DSS dataset for  $D_R = 70\%$  is still incomplete, but available data for specimens subjected to high CSR suggests a deviation from the trend portrayed by the  $q_{c1Ncs}$ -based curves, with a sharp increase in slope for less than 15 loading cycles. The reasons behind this discrepancy will be investigated following the completion of the present test series.

#### 4 CONCLUSIONS

A series of cyclic DSS tests on specimens of a clean sand from Christchurch was performed as part of a study on the liquefaction behaviour of Christchurch natural soils. The tests provide reference behaviour for clean sand at relative density of 50%, 60% and 70% using cyclic DSS tests. Future developments include the performance of a small number of additional tests on the same material, so as to develop a robust dataset on the cyclic response of Christchurch clean sands and provide a reference benchmark liquefaction resistance which will be used in a comparative evaluation of subsequent tests on reconstituted and undisturbed specimens of fines-containing sands.

#### 5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by the Earthquake Commission (EQC) and the Natural Hazards Research Platform (NHRP). The help and assistance provided by the lab technicians at the University of Canterbury, Mr Siale Faitotonu, Ms Nicole van de Weerd and Mr Michael Weavers, is gratefully acknowledged. The first author wishes also to thank the support provided by the UC Doctoral Scholarship.

#### REFERENCES

Beyzaei, C. Z et al. (2015) Liquefaction Resistance of Silty Soils at the Riccarton Road Site, Christchurch, New Zealand. *Proc. 6<sup>th</sup> ICEGE*, Christchurch, New Zealand, Paper No 616.

- Boulanger, R. W. (1990) *Liquefaction Behaviour of Saturated Cohesionless Soils Subjected to Uni-Directional and Bi-Directional Static and Cyclic Simple Shear Stresses*. PhD Thesis, University of California, Berkeley.
- Boulanger, R.W. & Idriss, I.M. (2014) *CPT and SPT Based Liquefaction Triggering Procedures*. Report No. UCD/CGM-14/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis.
- Cappellaro, C. & Cubrinovski, M. (2016) The Undrained Cyclic Response of Monterey Sand in Direct Simple Shear. *Proc. IYGPC*, Queenstown, New Zealand.
- Cubrinovski, M. et al. (2011) Geotechnical aspects of the 22 February 2011 Christchurch Earthquake. *Bulletin of the New Zealand Society of Earthquake Engineering*, 44(4), 205–26.
- Cubrinovski, M. et al. (2017) System response of liquefiable deposits. *Proc. PBDIII*, Vancouver, Canada.
- Cubrinovski, M. & Ishihara, K. (2000) Flow Potential of Sandy Soils with Different Grain Compositions. *Soils and Foundations*, 40(4), 103-119.
- Idriss, I.M. & Boulanger R.W. (2008) *Soil liquefaction during earthquakes*. Monograph MNO-12. Oakland, CA: Earthquake Engineering Research Institute; 261.
- Ladd, R. D. (1977) Specimen Preparation and Cyclic Stability of Sands. *Journal of the Geotechnical Engineering Division*, 103(6), 535-547.
- Mulilis, J. P. et al. (1977) Effects of Sample Preparation on Sand Liquefaction. *Journal of the Geotechnical Engineering Division*, 103(2), 91-108.
- Rees, S. (2010) *Effects of Fines on the Undrained Behaviour of Christchurch Sandy Soils*. PhD Thesis, University of Canterbury, Christchurch, New Zealand.
- Seed, H. B. (1979) Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground during Earthquakes. *Journal of the Geotechnical Engineering Division*, 105(2), 201-255.
- Stringer, M. et al. (2015) Liquefaction Characteristics of Christchurch Silty Soils: Gainsborough Reserve. *Proc. 6<sup>th</sup> ICEGE*, Christchurch, New Zealand, Paper No 726.
- Tatsuoka, F. et al. (1986) Cyclic Undrained Triaxial and Torsional Shear Strength of Sands for Different Sample Preparation Methods. *Soils and Foundations*, 26(3), 23-41.
- Taylor, M. (2015) *The Geotechnical Characterization of Christchurch Sands for Advanced Soil Modelling*. PhD Thesis, University of Canterbury, Christchurch, New Zealand.
- Vaid, Y. P. & Sivathayalan, S. (2000) Fundamental Factors Affecting Liquefaction Susceptibility of Sands. *Canadian Geotechnical Journal*, 37, 592-606.
- Verdugo, R. et al. (1995) Initial Soil Structure and Steady State Strength. *1<sup>st</sup> International Conference on Earthquake Geotechnical Engineering*, K. Ishihara, ed., Tokyo, Japan, 209-214.