The undrained cyclic strength of undisturbed and reconstituted Christchurch sands

M L Taylor, M Cubrinovski, and B A Bradley
Civil Engineering, University of Canterbury, New Zealand.
merrick.taylor@pg.canterbury.ac.nz (Corresponding author)

K Horikoshi
Tokyo Institute of Technology, Japan.

Keywords: liquefaction, cyclic triaxial test, Gel push sampling

ABSTRACT

This paper presents insights from recent advanced laboratory testing of undisturbed and reconstituted specimens of Christchurch silty-sands. The purpose of the testing was to establish the cyclic strength of silty-sands from sites in the Central Business District (CBD), where liquefaction was observed in 4 September 2010, 22 February 2011, and 13 June 2011. Similar overall strengths were obtained from undisturbed and reconstituted tests prepared at similar densities, albeit with higher variability for the reconstituted specimens. Reconstituted specimens exhibited distinctly different response in terms of lower compressibility during initial loading cycles, and exhibited a more brittle response when large strains were mobilised, particularly for samples with high fines content. Given the lower variability in natural sample response and the possibility of age-related strength to be significant for sites not subjected to earthquakes, high quality undisturbed samples are recommended over the use of reconstituted specimens to establish the cyclic strength of natural sands.

1 INTRODUCTION

The undrained cyclic strength of soils susceptible to liquefaction and cyclic softening is a key input for the assessment of liquefaction hazard, and the design of foundations including ground improvement treatments. It is commonly estimated using empirical correlations to field penetration tests (e.g. Cone Penetration Test, CPT, Youd et al. (2001)). Empirical cyclic strength curves are deliberately conservative due to the inherent scatter in the case history dataset, and have been inferred to correspond to a probability of liquefaction, P_L= 15% (Moss et al. 2006; Idriss & Boulanger 2010). A more accurate and precise estimate of cyclic strength may be provided by direct testing in the laboratory (e.g. cyclic triaxial testing (CTX), ASTM D5311 2004), however, this is usually reserved for soils that fall outside the typical soil types found within empirical datasets (i.e. fines-containing sands or gravelly soils), or for important projects.

Extensive and severe liquefaction was observed during the Canterbury earthquakes, particularly affecting deposits of fine sands and silty sands of recent fluvial or estuarine origin (Cubrinovski et al. 2011b). These soils are often highly variable, inhomogeneous (inter-bedded and laminated), exhibiting a wide range of fines content (*FC*[1]) that are typically non-plastic in nature. As a result, it is desirable to directly measure the undrained cyclic strength of these materials and compare with what might be inferred based on empirical prediction.

2 GEL-PUSH SAMPLING & CYCLIC TESTING

Undisturbed sampling was conducted at two sites of poor ground and building performance in the Christchurch Central Business District (CBD) in July-August 2011 (Cubrinovski et al. 2011a; Taylor et al. 2012a; Bray et al. 2013). Gel-push (GP) sampling was selected to obtain undisturbed samples from below the water table without resorting to expensive ground freezing.

[1] The *FC* in liquefaction analyses is defined as the % passing the #200 (75 μm) sieve, following US guidance on soil characterisation (i.e. ASTM D2487 2011).

Figure 1a shows the sampling operation diagrammatically, while Figures 1b and 1c present photos taken during the trial operation in the CBD. Undisturbed samples are required for a reliable measure of *in situ* cyclic strength, as soil 'fabric' (arrangement of particles) and 'ageing' effects are significant (Ishihara 1993). Details of the sampler design and appraisal of the obtained sample quality are given in Taylor et al. (2012b) . High quality samples of 'clean sands' (SP), 'silty sands' (SM) and 'silts with sand' (ML) were obtained from one of the two examined sites (e.g. Fig. 1d), but the other site had much poorer quality samples recovered due to some technical problems encountered.

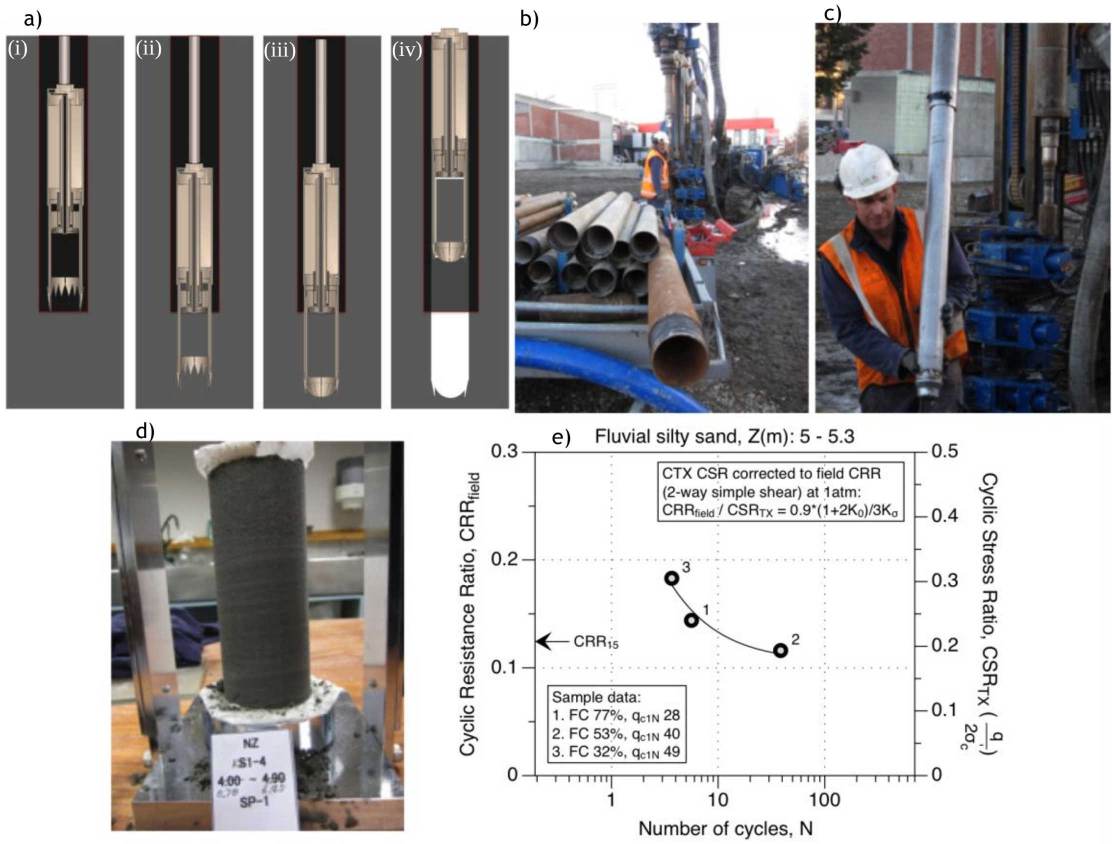

Figure 1: a) Illustration of the stages of operation of a GP-S type JPN sampler; (i) lowered down cased hole; (ii) pushed into virgin soil; (iii) closure of core catcher; (iv) removal to the surface (after Lee, 2011). (b) Drilling rig mobilised in the Christchurch CBD. (c) Removal of GP-S sampler from down the hole. (d) Trimmed sample showing natural structure of finely laminated silt and fine sand preserved. e) Cyclic strength curve for a single layer, with test data varying with fines content (*FC* 32-77%) and cone resistance (q_{c1N} 28-49).

The GP samples were tested (CTX) in order to determine cyclic strength curves, with results presented by Taylor et al. (2013). Typically three tests (minimum) on uniform samples (composition, density), performed at different cyclic stress amplitudes are required to reliably establish a cyclic strength curve over a relevant number of loading cycles, as shown for a single layer in Fig. 1e. The inherent natural variability over a relatively small depth in undisturbed samples of silty-sands makes the interpretation of cyclic tests more challenging than that for uniform deposits. Taylor et al. (2013) present alternative interpretations of the natural sample data including by depth/ soil horizon, and grouping by 'soil type' for comparison to the empirical procedure. A key finding was that Christchurch silty sands appeared to exhibit lower cyclic strengths than would be estimated using the semi-empirical method based on CPT correlation to cyclic strength. Further reconstituted testing allows comparison to the GP sample test data and can help support the reliability of the initial findings presented by Taylor et al. (2013) as well as gain insights into the effects of fabric on the cyclic strength.

3 CYCLIC TRIAXIAL TESTING OF RECONSTITUTED SPECIMENS

Due to the limitations of grouping GP samples by 'soil type', further CTX tests on reconstituted specimens have been conducted for selected 'soil class' groups, i.e. based on grainsize distribution and plasticity, similar to the basis of the USCS system (ASTM D2487-11), prepared at similar relative density to the GP samples. Reconstituted tests are typically used to investigate a specific aspect of soil response. For example, Rees (2010) and Arefi et al. (2012) used reconstituted samples of Christchurch silty sand to investigate the effect of non-plastic fines (ranging from 1 to 30% *FC*) on the monotonic and cyclic undrained response and dynamic soil properties, respectively. In this study the GP samples were grouped into four 'soil class' groups; clean sands, *FC* < 5% (SP); silty sands, *FC* 15-20% (SM_{15-20}); silty sands, *FC* 30-50% (SM_{30-50}); silt with sand, *FC* 50-80% (ML). These groupings were used as a basis of selecting representative reconstituted specimens.

3.1 Apparatus Capability

Cyclic strength testing was performed at the University of Canterbury's geomechanics research laboratory on a recently acquired (2009) dynamic triaxial testing apparatus developed by Seiken Inc. of Japan. It allows the researcher to conduct stress or strain controlled monotonic and cyclic triaxial tests, the latter over a range of frequencies (0.001- 9 Hz) of applied sinusoidal axial loading at a desired amplitude. The limiting cell pressure is 1 MPa, and the load-cell is rated to 2 kN at 1 N level of precision. For dynamic testing the maximum range of the load cell is reduced to 500 N with increased measurement precision to 0.25 N. The maximum travel of the loading ram relative to the specimen height allows for up to 25% strain under monotonic loading, measured with an external displacement transducer (LVDT). Small strain measurement is provided by an in-cell high resolution electromagnetic proximity sensor, mounted on the top platen, capable of measuring +/- 1 mm of displacement in 0.0005 mm increments, enabling measurement to within the elastic range (1 E-5 strain), apart from the influence of bedding errors. In addition, bender elements mounted in the platens allow for shear wave velocity measurement, and direct evaluation of small strain stiffness G_0.

3.2 Materials tested

The GP samples of fluvial materials were highly variable in terms of *FC*, with interbedded layers of non-plastic silt and fine sand occurring throughout the sampled profile. The gradation curves of all GP tested samples, plotted in Fig. 2, were obtained following testing by sieving and particle size analysis of the retained fines using the laser diffraction method. The four plotted groups represent the 'soil class' groupings used as a basis for reconstituted specimen testing. A single specimen from among the group was selected as representative rather than by mixing samples.

3.3 Sample preparation

The moist tamping (MT) technique with 10% moisture and 1% undercompaction (Ladd 1978), was adopted to form uniform reconstituted samples. This method was selected in order to readily target a desired sample density, and to enable comparison to previous testing by Rees (2010). It is noted that, for sands with fines, the MT technique artificially mixes the fines randomly amongst the sand grains, whereas it was observed that the undisturbed samples are finely interbedded/ laminated, which occurs when the grains fall out of suspension under a declining hydraulic gradient (e.g. Fig 1d).

3.4 Consolidation and Compressibility

Fig. 3 presents a comparison of the isotropic compressibility, M_v, of GP and MT samples sorted by soil class, measured during consolidation prior to shearing, where M_v is calculated from void ratio change from e_0 to e_1 due to increase in confining stress from σ'_0 to σ'_1:

$$M_v = \frac{1}{1+e_0}\left(\frac{e_0-e_1}{\sigma'_1-\sigma'_0}\right) \qquad [1]$$

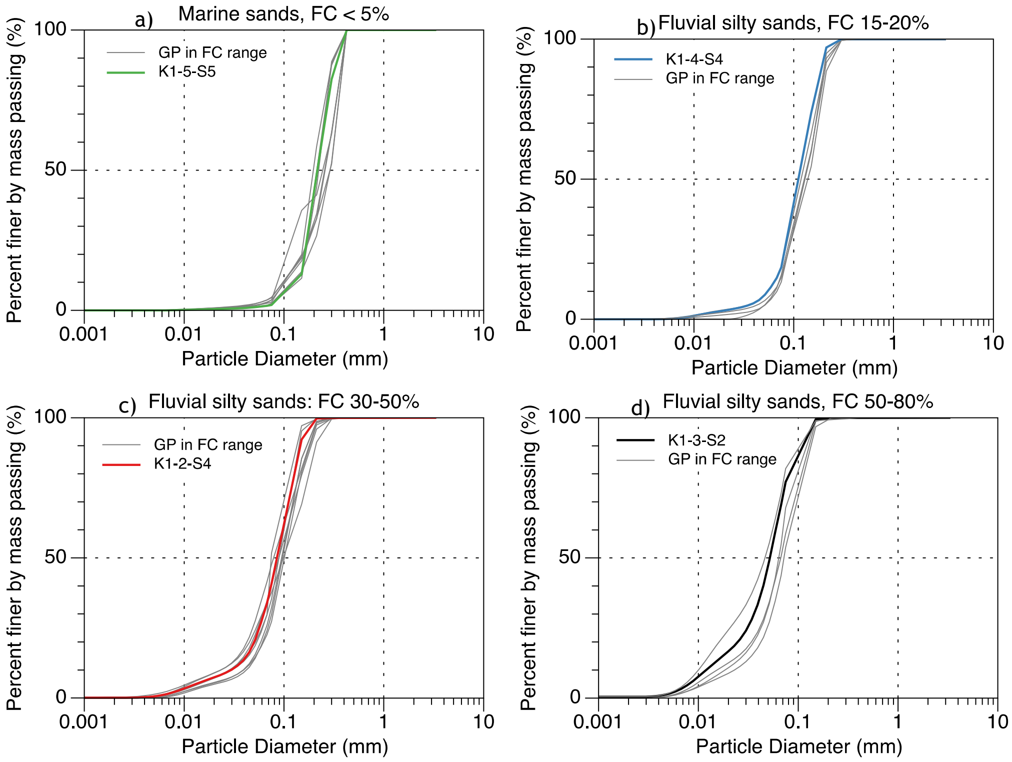

Figure 2: Particle size distribution curves of GP samples tested from a site north of the Avon River, binned into similar 'soil class' based on Fines Content as a proxy for soil gradation. Selected 'representative sample' shown in bold/ colour. a) *FC* <5%; b) *FC* 15-20%; c) *FC* 30-50%; d) *FC* 50-80%.

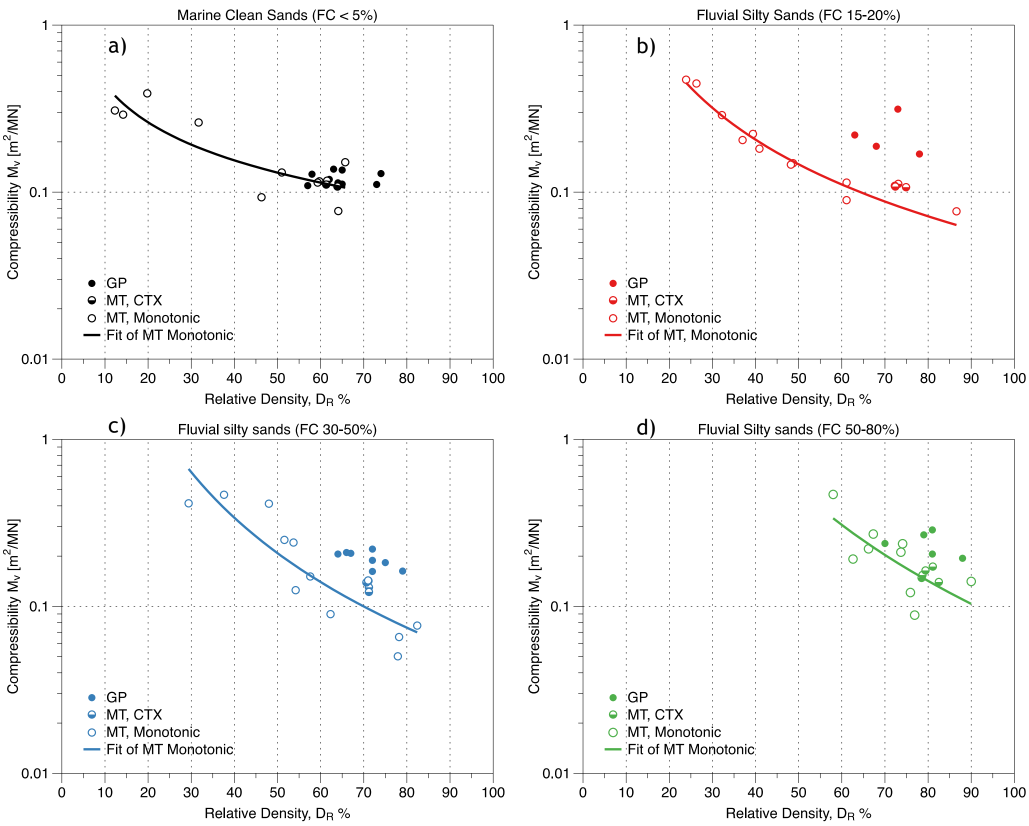

Figure 3: Comparison of compressibility of representative soil class groups during consolidation of MT and GP samples, (a) Clean marine sands *FC* <5%, (b) fluvial silty sands *FC* 15-20%, (c) *FC* 30-50%, (d) fluvial silt with sand *FC* 50-80%.

The soils with higher *FC* display a higher compressibility for a given relative density. Importantly, GP samples (solid symbols) exhibit higher compressibility relative to MT samples (open & half-shaded symbols). This discrepency is greatest for samples with moderate *FC* (15-20%, then 30-50%, then 50-80%), with no apparent difference for the clean sands. We attribute this effect to the inhomogeneity of the GP samples, with silt laminations exhibiting higher compressibility than when the grains are randomly distributed throughout an MT prepared sample. The impact of inhomogeneity is strongest in materials with moderate fines, reducing with higher fines content (as the effect of fines dominates regardless of structure), and is not relevant for clean sands. This hints at possible differences in the cyclic response of MT and GP samples on account of soil 'structure' (i.e. layering) and fabric variances. We might expect that the differences in structure would result in a slightly higher tendency to generate excess pore water pressure in GP samples, with resulting lower cyclic strength, particularly for the GP samples with a moderate fines content.

3.5 Reconstituted cyclic triaxial tests

3.5.1 Cyclic strength curves

Figure 5 presents a comparison between testing performed on GP and MT samples. It can be seen that the GP & MT results align reasonably well (when grouped by soil class), allowing for some variance due to relative density, and obvious differences in structure and fabric (Fig. 4). However, the attempts to reproduce the strength curves using MT samples resulted in a wider variation in test results, compared to the original GP samples (Fig. 5). At first appraisal the effects due to fabric appear subtle, with ageing effects likely insignificant. The large strains induced in the near surface soils by recent earthquakes (sand boiling observed post 22-Feb and 13-Jun-2011 quakes, with sampling undertaken in early August 2011), would be expected to have erased any 'age'-related strength that existed prior to the earthquake sequence, such that any contribution to the cyclic strength at that time remains unknown.

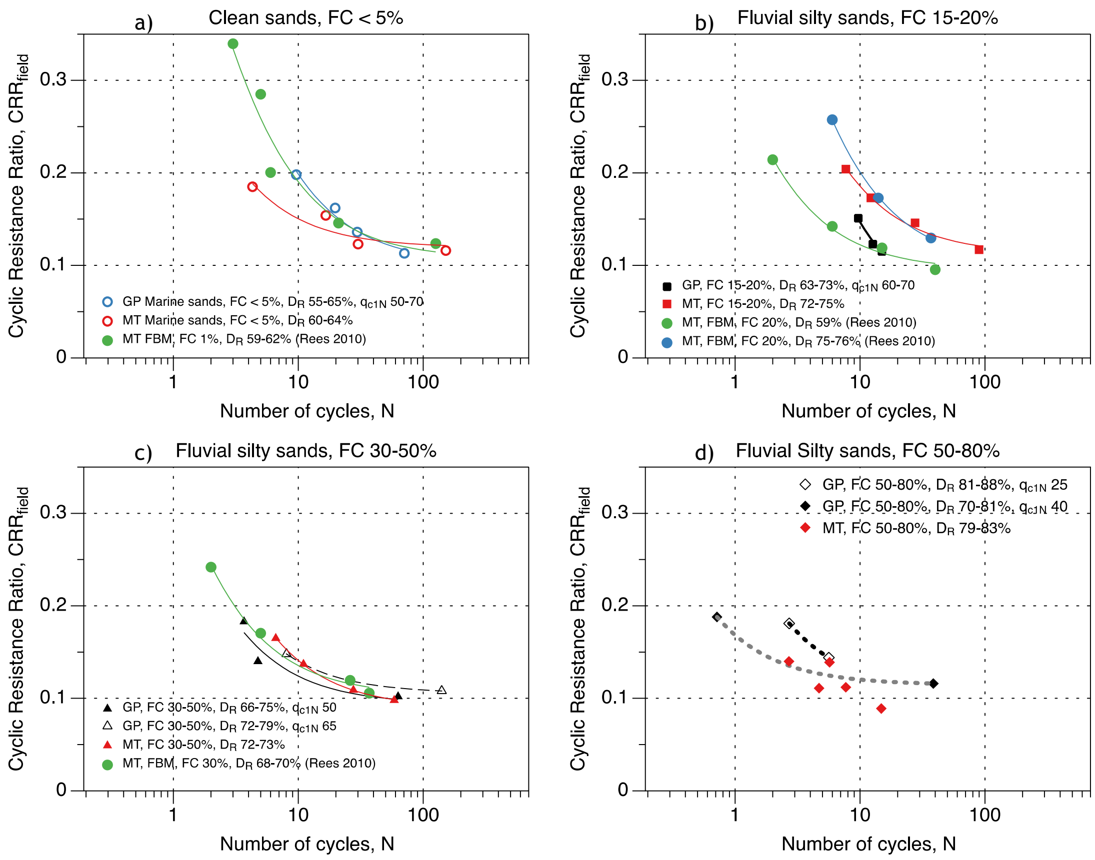

Figure 4: Comparison of GP & MT sample cyclic strength curves including relevant test data on from the study by Rees (2010) on similar soils (FBM). (a) Clean sands *FC* <5%, (b) Silty sands *FC* 15-20%, (c) *FC* 30-50%, (d) fluvial silt with sand *FC* 50-80%.

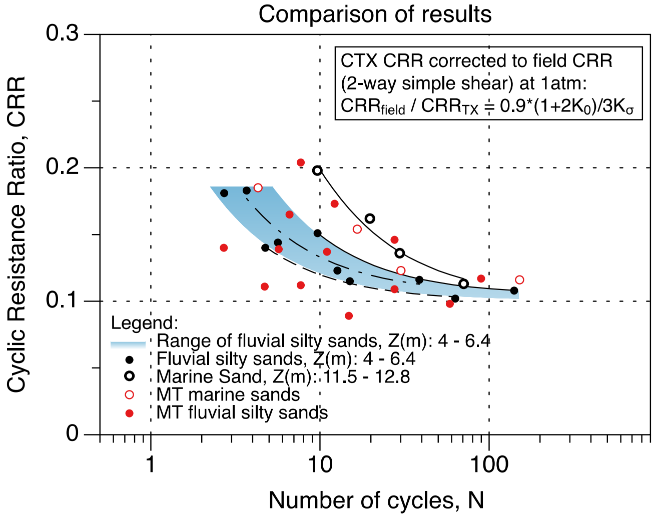

Figure 5: Variability of GP and MT sample cyclic strength data.

3.5.2 Small to intermediate strain response

While measurements of shear wave velocity (V_s) did not show any clear differences between GP and MT samples for the respective soil class groups, by comparing the development of strain within GP and MT samples during the cyclic test we may gain further insights into differences in effects of fabric at small to large strains. Figure 6 presents the development of strain up to 5% in Double Amplitude (DA) for GP samples, and MT samples from the same type soil (15-20%, and 50-80% shown) and similar density. GP samples exhibit a higher initial increase in strain than MT samples (consistent with the observation of higher compressibility during consolidation), but this was followed by declining rate of strain development towards 5% DA, indicating a high degree of granular interlock in the sample, resisting the applied shear stress. MT samples, by contrast, exhibit lower initial strain, but a progressive decrease in stiffness with number of cycles toward 5% DA, particularly as the stress path approaches the failure surface (envelope), indicating a weaker fabric to resist the applied shear stress. For the GP sample, the rate of increase of the excess pore pressure diminishes with approach to the zero effective stress state, due to increasing dilatancy at higher stress ratios, but such a rate reduction is not observed for the MT sample, which also exhibits a significantly more brittle response. The 50-80% fines MT sample in particular exhibited a very brittle response from ~1-2% DA strain, with rapid collapse and large strain development (in excess of 10% DA strain).

3.5.3 Discussion

For ‘silt with sand’ (ML) samples the strength of the MT specimens is lower than the GP samples. During testing it was observed that a layer within the MT sample would initially soften and exhibit large strains (necking of sample), often suddenly within one cycle. This was a more brittle response than observed for all other specimens. This may be due to the artificial fabric created during MT sample formation that may be responsible for unstable force-chain networks when significant fines are present. By contrast, GP samples exhibit decreasing amounts of strain with successive cycles, indicating that further strain mobilises a more dilatant response from the soil, reducing further excess pore pressure development, softening and strain development with number of cycles.

From these observations we can conclude that the testing of undisturbed samples produces significantly reduced variation in cyclic strength estimates for natural deposits and avoids concerns over the stability of artificial fabrics created in the laboratory and the appropriateness of such testing for engineering practice. Provided undisturbed samples are carefully sampled, handled, and tested, significantly more reliable cyclic strengths may be determined, both for critical appraisal of cyclic strength of a material, but also for accurate calibration of numerical models used for forward prediction of ground and foundation performance.

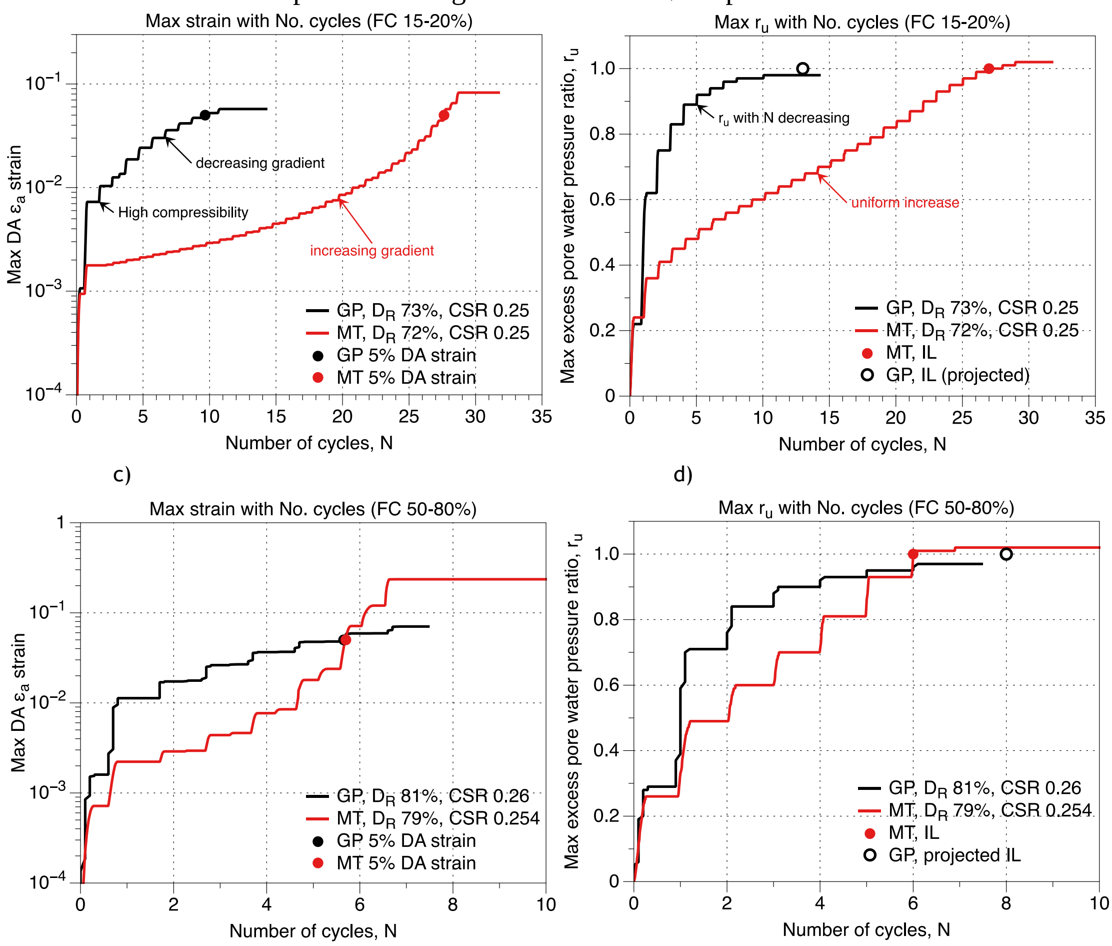

Figure 6: Comparison of strain and excess pore pressure development during undrained cyclic loading of GP samples (black) and MT samples (red) prepared at similar densities and tested at similar cyclic stress ratios; (a) silty sands (FC 15-20%) DA strain, (b) silty sands (FC 15-20%) r_u, (c) sandy silt (FC 50-80%), DA strain, (d) sandy silt (FC 50-80%) r_u. D_R = Relative Density, r_u = excess pore pressure ratio u_e/σ'_3, IL = Initial Liquefaction (r_u =1).

4 SUMMARY AND CONCLUSIONS

High quality undisturbed (GP) samples of Christchurch sands have been tested for undrained cyclic strength and compared to the empirical method used in engineering practice. The comparison highlights the complexity in interpreting the cyclic strength data for natural materials with high variability in fines content. Further tests on reconstituted samples of selected representative soil gradations aim to confirm findings of GP sample behaviour, and provide insight into the effect of *in situ* fabric on the cyclic strength of these materials.

GP and MT samples exhibit similar overall cyclic strength, providing weight to the finding that Christchurch silty sands and sandy silts exhibit lower strength than would be predicted by the empirical method. Reconstituted specimens however exhibited distinctly different response in terms of lower compressibility during initial loading cycles, and exhibited a more brittle response when large strains were mobilised, particularly for samples with high fines content, on account of both natural inhomogeneity of sample structure and ‘fabric’ differences. Given the lower variability in natural sample response and the possibility of age-related strength to be significant for sites not subjected to earthquakes, high quality undisturbed samples are recommended over the use of reconstituted specimens to establish the cyclic strength of sands.

5 ACKNOWLEDGEMENTS

New Zealand Government support (New Zealand Earthquake Commission (EQC), Environment Canterbury, and the University of Canterbury) for this research is gratefully acknowledged.

REFERENCES

Arefi MJ, Cubrinovski M, Rahman MM 2012. *Effects of fines on stress-strain behaviour of sands*. Australia-New Zealand Conference on Geomechanics , Ground Engineering in a Changing World. Melbourne, Australia.

Bray JD, Cubrinovski M, Zupan J, Taylor ML 2013. Liquefaction Effects on Buildings in the Central Business District of Christchurch. *Earthquake Spectra* (Submitted).

Cubrinovski M, Bray JD, Taylor ML, Giorgini S, Bradley BA, Wotherspoon L, Zupan J 2011a. Soil Liquefaction Effects in the Central Business District during the February 2011 Christchurch Earthquake. *Seismological Research Letters* 82(6): 893-904.

Cubrinovski M, Bradley BA, Wotherspoon L, Green RA, Bray JD, Wood C, Pender M, Allen J, Bradshaw AS, Rix G and others 2011b. Geotechnical Aspects of the 22 February 2011 Christchurch Earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering* 44(4): 205-226.

Idriss IM, Boulanger RW 2008. *Soil Liquefaction during Earthquakes*. Oakland, CA, Earthquake Engineering Research Institute.

Idriss IM, Boulanger RW 2010. *SPT-Based Liquefaction Triggering Procedures*, Centre for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, California.

Ishihara K 1993. Liquefaction and Flow Failure during Earthquakes. *Géotechnique* 43(3): 351-415.

Ladd RS 1978. Preparing Test Specimens Using Undercompaction. *Geotechnical Testing Journal* 1(1).

Moss RES, Seed RB, Kayen RE, Stewart JP, Der Kiureghian A, Cetin KO 2006. CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. *Journal of Geotechnical and Geoenvironmental Engineering* 132(8): 1032-1051.

Rees S 2010. Effects of fines on the undrained behaviour of Christchurch sandy soils. *Doctor of Philosophy thesis*, University of Canterbury, Christchurch. 282 p.

Taylor ML, Cubrinovski M, Bradley BA 2012a. Characterisation of Ground Conditions in the Christchurch Central Business District. *Australian Geomechanics Journal* 47(4): 43-57.

Taylor ML, Cubrinovski M, Haycock I 2012b. *Application of new 'Gel push' sampling procedure to obtain high quality laboratory test data for advanced geotechnical analyses*. 2012 New Zealand Society for Earthquake Engineering Conference. Christchurch, New Zealand, NZSEE.

Taylor ML, Cubrinovski M, Bradley BA 2013. *Cyclic strength testing of Christchurch sands with undisturbed samples*. 2013 New Zealand Society for Earthquake Engineering Conference. Wellington, NZSEE (Oral Paper No. 11).

Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Liam Finn WD, Harder L.F, Jr., Hynes ME and others 2001. Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental Engineering* 127(10): 817-833.