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Liquefaction Resistance of Christchurch CBD soils

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ABSTRACT

The liquefaction-susceptible soils that underlie the Christchurch CBD have been evaluated within a comprehensive field (CPT, borehole, shear-wave velocity) and laboratory-testing programme. Sampling sites exhibited extensive ground damage following the earthquakes, requiring demolition of multi-storey commercial buildings. Liquefaction resistance was evaluated by direct measurement using cyclic triaxial testing on undisturbed specimens obtained from 2 to 14 m depth of CBD deposits, using novel Gel Push (GP) sampling. Tested samples cover a broad range of soils from clean sands (SP) to silty sands (SM), sandy silts (ML), with fines contents (typically non-plastic) ranging from 1 – 98 %. Cyclic strength testing allows comparison to the empirical correlations based on case-history data, which now include case histories from the recent events in Christchurch, New Zealand. While generally good agreement is obtained for clean sands, comparison of sands with high non-plastic fines indicate more research is warranted to clarify the cyclic strength of these deposits, given their prevalence in Christchurch.

Introduction

Following the 2010-2011 Canterbury Earthquake Sequence (CES) a research investigation was conducted to better characterise the deposits most at risk of soil liquefaction. Two sites in the Christchurch Central Business District (CBD) that exhibited extensive liquefaction adversely impacting building foundation performance were targeted for detailed investigations: CPT testing; borehole drilling; shear wave velocity (V_s) testing; and Gel Push (GP) sampling (Bray et al. 2014, Taylor et al. 2012). GP is a new method for obtaining undisturbed specimens of sandy soils from below the water table, and trialled in Christchurch following promising work by Kiso Jiban Consultants (Japan), and Huang et al. 2008 (Taiwan). The GP samples were subjected to cyclic (CTX) and monotonic triaxial loading, and compared to a suite of tests on reconstituted specimens of representative GP samples. This comparison identifies the influence of natural features (structure, fabric) on the soil response. The lab results, coupled with field profiling data, and complimented with soil index properties (gradation, specific gravity (G_s), Atterberg limits, max & min void ratio (e_{max}, e_{min}), and grain shape) provide a comprehensive soil characterisation. This paper summarizes the project, some of the key findings, and proposed future research directions.

Geology of Christchurch CBD soils

The Christchurch CBD was founded by European settlers (1850) on the nearest high-dry land above the coastal swamps suitable for establishing the township (Wilson 1989). It is described as an "island" of gravel within the swamp, the easternmost extent of a legacy flood channel of the Waimakariri River. Either side of these gravel channels are overbank deposits of sand and silt, with clays/ organics

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found further from the recent channels. Between flood events, the spring-fed Avon River meanders west-to-east through the city, developing large meander loops on its way to the estuary and Pacific Ocean.

Post-quake reconnaissance and ground investigations

While evidence of minor sand boiling and surface water from liquefaction were commonly encountered across Christchurch including the CBD, observations of extensive and severe soil liquefaction were isolated to particular regions of the CBD (Cubrinovski et al. 2011), notably adjacent to recent gravel channels that incur into the CBD, where flood overbank deposits of sand and silty sands have accumulated without capping by a low permeability crust. This includes Kilmore Street east of Colombo, Salisbury and Peterborough Streets east of Manchester, and within the Avon Loop, south of the Avon River between Barbadoes and Fitzgerald Streets (refer Figure 1). A smaller area of extensive liquefaction was also observed to the south of the recent gravel channel following the present Avon River course, on the corner of Madras and Armagh Streets. Extensive, severe and repeated liquefaction was observed in these areas affecting multi-storey buildings (piled and shallow founded), requiring demolition post-quake. Both the Kilmore and the Madras-Armagh areas were targeted for intensive CPT testing, boreholes and trial GP sampling (Bray et al. 2014). The typical soil profile from Kilmore Street, adjacent to Transport House is shown in Figure 2, showing the thick profile (2 – 8 m) of silty-sands overlying clean sands.

Gel-push sampling and specimen quality

Cyclic testing of undisturbed samples provides a measure of *in situ* response, as soil ageing, fabric and layering can be significant (Ishihara, 1993). GP sampling was selected to obtain undisturbed samples from below the water table without resorting to expensive ground freezing.

Figure 3a) depicts the GP-S (piston-type) sampling procedure, while Figures 4b) and 4c) show the sampling trial in the CBD.

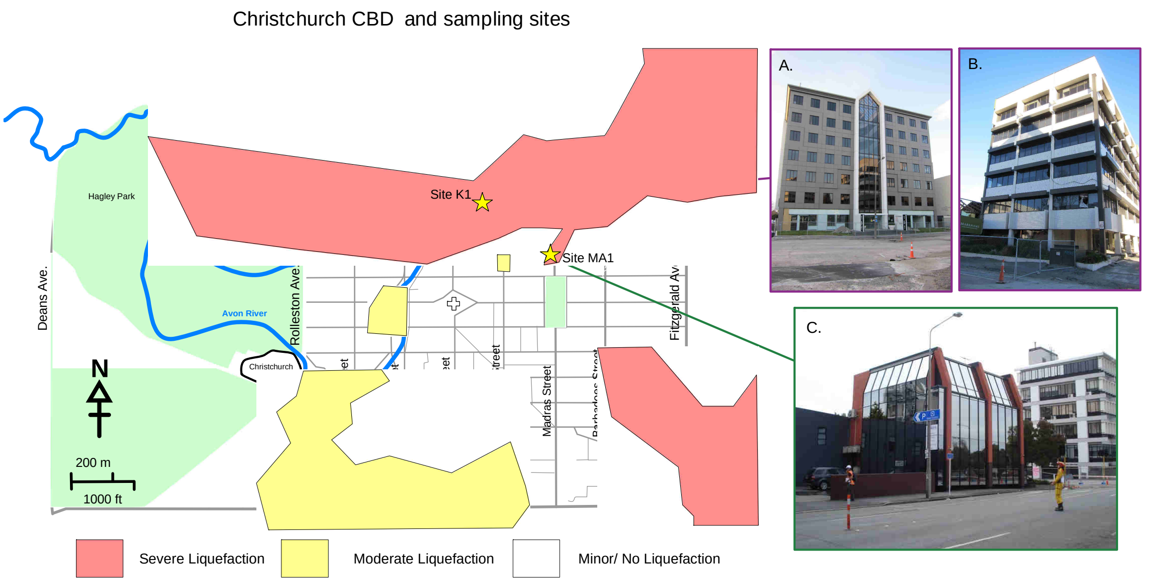

Figure 1: Christchurch CBD map with liquefaction observations and location of sampling sites (yellow stars). Photos: A) Transport House, 151 Kilmore Street, (B) Markhams Building, 144 Kilmore Street;

(C) Amicus House, 240 Armagh Street (near) and Trade Union Building, 199 Armagh Street (far).

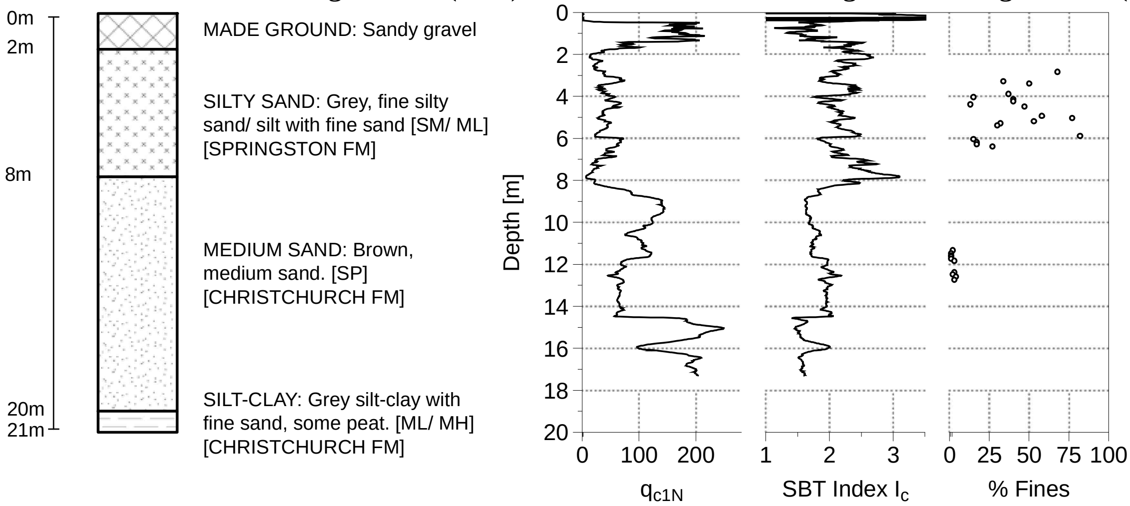

Figure 2: Soil profile at site K1, on Kilmore Street between Colombo and Manchester Streets.

For details of GP-S trials and initial sample quality appraisal refer Taylor et al. (2012a), a detailed evaluation is presented by Taylor (2014). Generally good quality silty-sand samples were obtained, with well-preserved soil fabric and structure (refer Figure 4E), with a close match between field and lab-measurements of V_s. The V_s test results also indicate that ageing effects are likely to have been erased/ reset during the large shearing induced during the recent quakes, or that they were not significant prior to the quakes (McGann et al. 2014, pp. 20-21). Further evaluation of the GP sampler is ongoing with recent field trials at further sites around Christchurch.

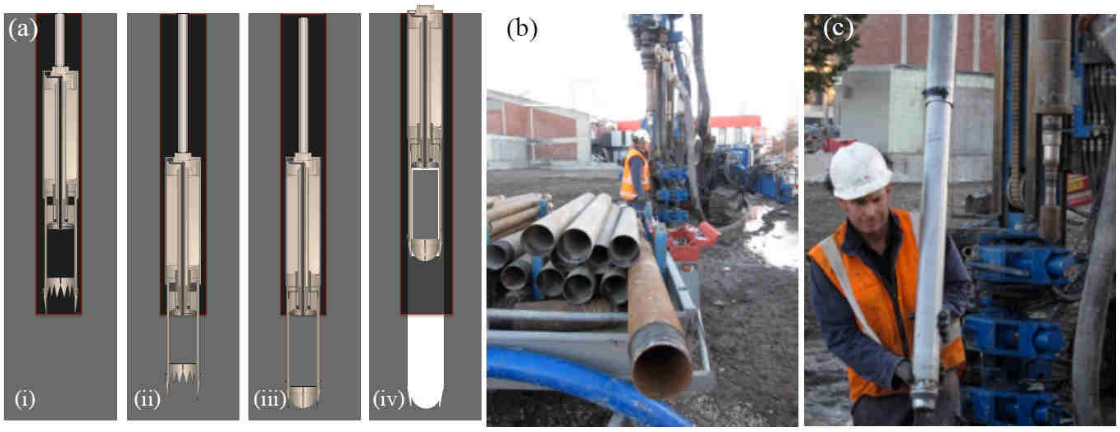

Figure 3: (a) Diagrammatic representation of GP-S sampling downhole (i) insertion at base of drilled hole (ii) advance into virgin soil (iii) closure of core catcher (iv) retrieval of sample. (b) drilling on site in Christchurch CBD (c) retrieval of GP sampler.

Figure 4A shows GP sample harvesting from sample liners, with SM and SP samples shown (Figure 4B and C resp.). The samples were trimmed from 70mm dia. x 120 high to 50 mm dia. x 100 high and mounted in the triaxial apparatus for testing (Figure 4D, E and F). Note the highly stratified structure of the trimmed SM sample is well preserved indicating high quality (Figure 4E). Fluvial sands of the

Springston Formation (*Sp. Fm*) exhibited a wide range of fines contents (*FC*, % passing 75μm sieve) where fines were largely non-plastic silt (
Figure 5A).

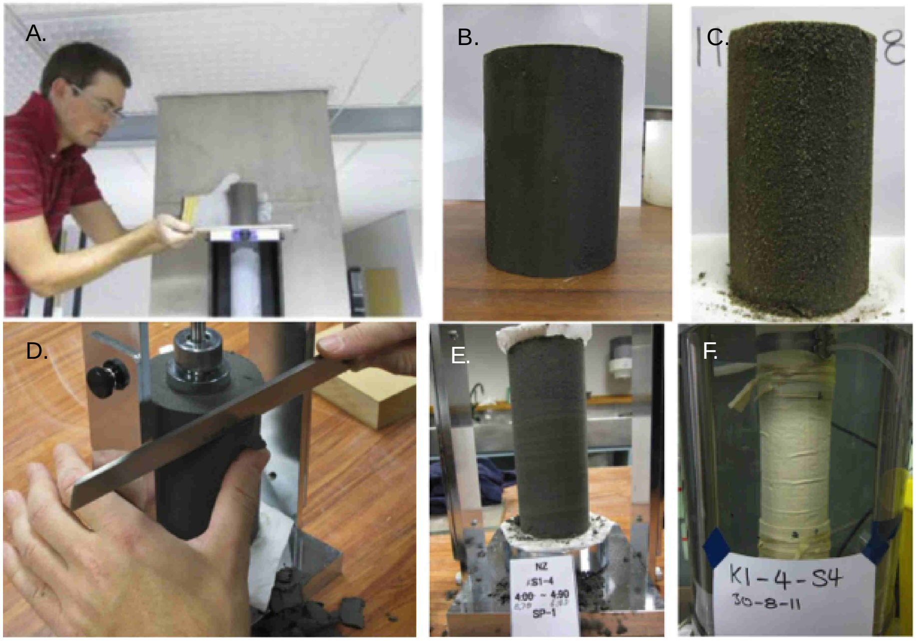

Figure 4: A: Harvesting undisturbed samples; B) silty sand (SM) sample; C) clean sand (SP) sample; D) trimming operation; E) trimmed silty sand sample; F) set-up in triaxial apparatus.

Figure 5 presents the particle size distribution curves (PSD) for samples obtained from K1 site (Kilmore St.), which are fairly uniformly graded. The marine beach sands (
Figure 5B, Christchurch Formation, *Ch. Fm.*) were clean of fines, having been deposited under high-energy wave loading, and existed *in situ* at higher densities (D_R > 60%). Each GP sample was measured for V_s (using bender elements), e_{max}, e_{min}, and G_s. Atterberg Limit tests targeted soils with some noted plasticity at the Madras-Armagh site.

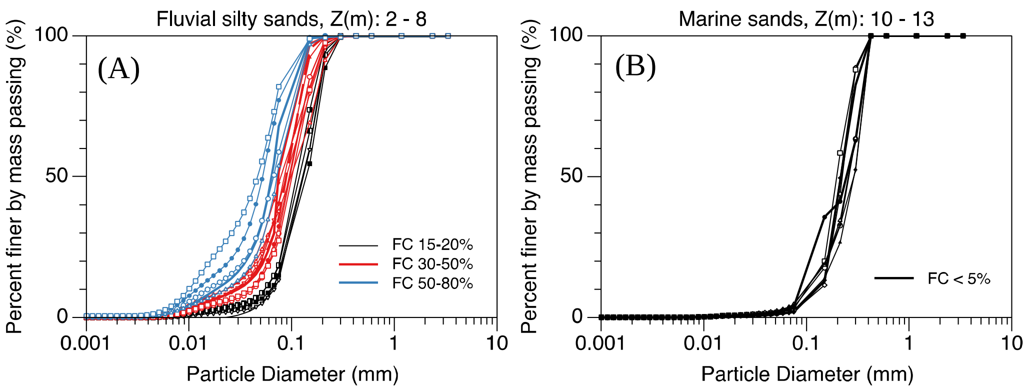

Figure 5: Particle size distribution curves of GP samples tested from Kilmore St. at depths (Z) noted.

Cyclic Response of GP Samples

The results of CTX testing are interpreted by constructing a cyclic strength curve (cyclic stress ratio *CSR* vs. number of cycles, N_c, to induce 'liquefaction', defined by strain-based proxy of 5 % double amplitude axial strain, DA ε_a). Cyclic strength curves are shown in Figure 6, constructed from 3 - 4 No. CTX tests on GP samples of silty-sand from the same sample tube/ depth. Note the variation in sample *FC* and q_{c1N}, which is undesirable for understanding the influence of these factors on the cyclic strength requiring further interpretation to normalise the data.

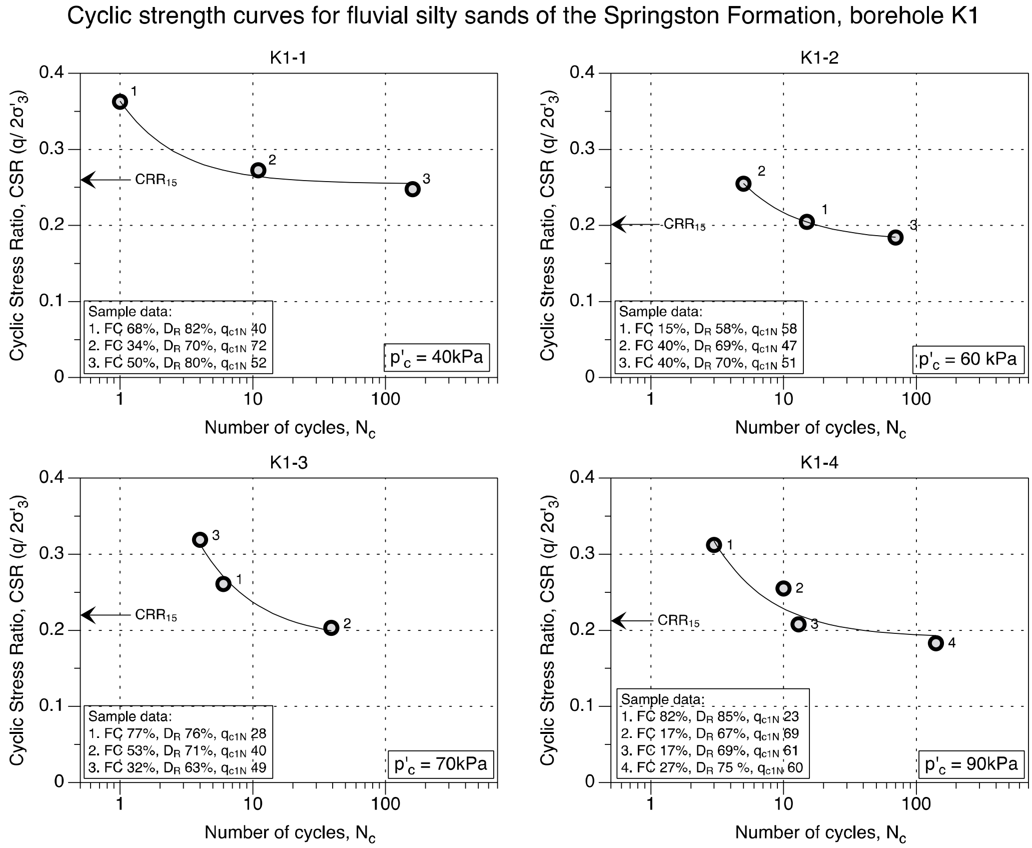

Figure 6: Cyclic strength curves constructed per sample tube. Intercept at 15 cycles (CRR_{15}) indicated.

Interpreted Response of Christchurch Silty Sands

Figure 7A presents all K1 test results compared following correction for the field condition (C_r factor, refer inset for relationship) and for confining stress to 1 atm. using K_σ factor after Idriss and Boulanger (2008). The blue shaded region is for *Sp. Fm.* silty sands. Despite variations in *FC* and density, the normalized cyclic strengths of the *Sp. Fm.* samples were quite uniform, while the clean sands (*Ch. Fm.*) exhibited higher cyclic resistance.

Natural variations in soil gradation; state; layering; and fabric with depth add complexity to characterising the effects of *FC* and density on the cyclic strength of GP samples. The adopted approach involved using *FC* to group GP samples within a geological unit by 'soil type', similar to USCS class (SP, SM, ML). Once corrections applied, and results grouped in this manner, alternative cyclic strength curves were constructed (Figure 7B). Selected 'representative' samples from each *FC* range were subjected to multiple tests on moist-tamped (MT) reconstituted specimens. These were also corrected to field CRR_{15} values. Both sets of results have been compared to the empirical liquefaction-triggering curve (Taylor et al. 2015), with results summarised herein. The test site from Madras-Armagh GP sampling site (MA) provided test results that included soils that had low-plasticity (PI 5-13), and these samples exhibited notably higher cyclic resistance than non-plastic soils (cyclic strength curves not presented in this paper).

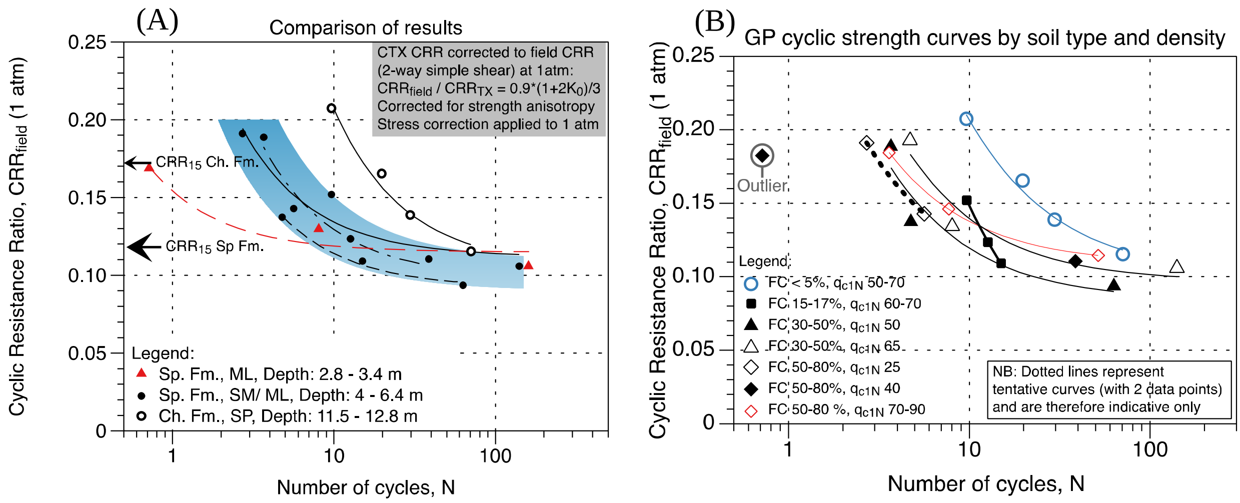

Figure 7: A) Comparison all cyclic strength test data for Kilmore Street site, corrected for the field condition and normalised for confining stress. B) Data points when sorted by soil type and density

Comparison to the empirical liquefaction triggering curve

The CPT-based empirical liquefaction-triggering curve is plotted in CRR_{15}, q_{c1N} space. To plot cyclic test data on the plot requires correlation between q_{c1N} and specimen D_R, known to be a function of the soil gradation (Cubrinovski & Ishihara 1999). The best quality GP samples (known *FC*, D_R, and adjacent q_{c1N} data) were thus used to derive a soil-specific correlation as a function of *FC* (Taylor et al. 2015). This allowed for estimates of the equivalent q_{c1N} corresponding to the CRR_{15} values derived from the cyclic strength curves for similar soil type. By plotting the data on the triggering curves corresponding to the *FC* of the specimens, an independent check of the empirical curve may be considered for the soil. There is acknowledged a significant degree of uncertainty with the correlations and with the adopted C_r factor, however it is a useful exercise to indicate possible trends or areas requiring further consideration. Plots are presented in Taylor et al. (2015) for each *FC* range considered (*FC*<5%, 15-30%, 30-50%, 50-100%).

Figure 8 (this paper) presents the liquefaction triggering plot of Idriss and Boulanger (2008) (IB08) for *FC* > 35% (probability of liquefaction, P_L 15%, 50% and 85% shown which present the expected range after Boulanger & Idriss, 2012) with data points (triangles) from cyclic strength testing of soils with *FC* 30 – 50 % range, error bars indicate expected uncertainty in the correlations adopted. The results indicate that for high *FC* silty sands, the position of the test-derived data points fall well below the expected range (i.e. approx. coinciding with the P_L of 50% curve, e.g. as shown by Boulanger & Idriss (2014, p.97) for individual clean sands). The exception being one MA data-point (inverted blue triangle) shown that exhibited PI of 8, and fell in the expected range. Of note, a study by Carraro et al. (2003) on Ottawa sand with non-plastic fines (silica flour), showed higher *FC* resulting in a marked shift of the triggering curve towards the right, which Boulanger and Idriss (2014) noted as being due to drained soil response in the study, whereas undrained behaviour would result in lower q_{c1N} in the field (i.e. contractive response with excess pore water pressure development). While that trend is not what is shown here –with sand with high *FC* exhibiting higher CRR_{15} for a given q_{c1N} than clean sands, and the *in situ* state parameter estimates from CPT in this soil were negative indicating a dilative response, there remains a significant shift to the right from what is expected from the empirical triggering method. Possible reasons include larger uncertainty in C_r than expected, sampling disturbance affecting the adopted correlation to q_{c1N}, as well as limitations of the case-history dataset with regards to characterising the influence of fines on the CPT-based liquefaction triggering curve.

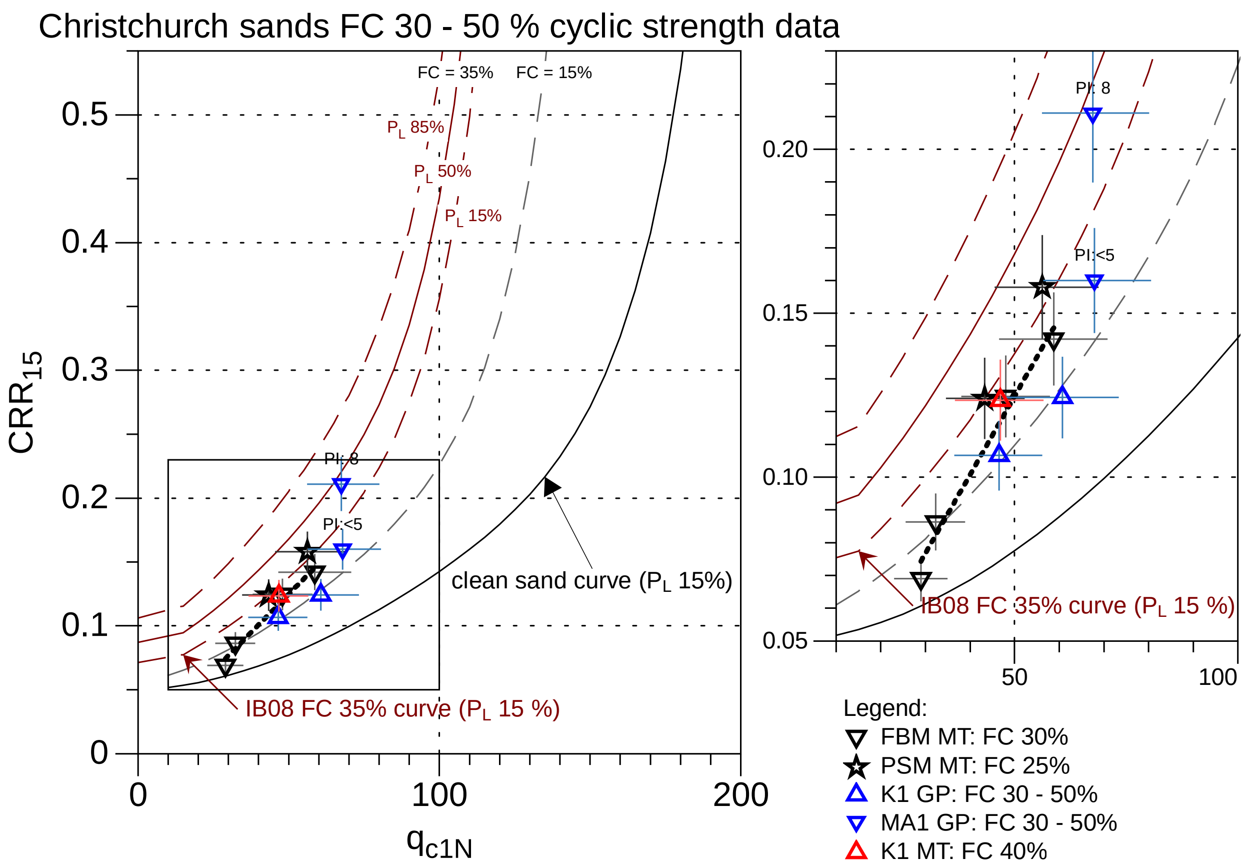

Figure 8: Comparison of collated cyclic test data for Christchurch sands with FC 30-50%, and IB08 liquefaction triggering curve. PSM and FBM test data from Rees (2010). MT = moist tamped. GP = gel push

Summary and Conclusions

An investigation of the cyclic resistance of sands from Christchurch CBD has been conducted using state-of-the-art methods, including field profiling (CPT, borehole, V_s), and high quality undisturbed sampling (GP piston sampler). The GP samples are from areas in the CBD significantly affected by liquefaction during the Canterbury Earthquakes 2010-2011. Cyclic triaxial testing and complimentary index testing was conducted and results interpreted for the field condition. The data allows for comparison to the simplified liquefaction-triggering curve, as used extensively in engineering practice. A comparison is presented for soils with high non-plastic fines content. The results from both GP and reconstituted specimens (MT) exhibit lower cyclic resistance than the empirical triggering curve, an exception being a specimen with some noted plasticity. The results suggest that the influence of fines on the liquefaction triggering method is worthy of further investigation –particularly due to the paucity of case history data used to define the triggering curve for soils with high *FC* and low/ no plasticity. Factors affecting the sample response (sample disturbance, correction to the field condition) may also affect the comparison presented. Research in these matters is ongoing at the University of Canterbury.

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