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CYCLIC SHEAR LOADING RESPONSE OF FRASER RIVER DELTA SILT

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SUMMARY

An experimental research program has been undertaken to study the earthquake response of Fraser River Delta silt. The mechanical response of the silt is investigated using the direct simple shear (DSS) device, and this paper presents the results from constant volume cyclic DSS tests conducted on samples that were normally consolidated without initial static shear stress bias. During cyclic loading, the silt material developed significant shear strains due to cyclic mobility with zero, or near zero, transient effective stress conditions, and the response is much similar in form to the observed cyclic shear behaviour of dense (dilative) sands. Because of the dilative nature, Fraser River silt exhibits a significantly higher cyclic shear resistance in comparison to that for loose Fraser River sand in spite of the relatively higher void ratio in the former than the latter. The silt samples that developed high excess pore water pressures during cyclic loading experienced relatively large volumetric strains during post-cyclic consolidation suggesting significant changes to the particle structure due to liquefaction and subsequent reconsolidation.

INTRODUCTION

Earthquake-induced liquefaction is one of the primary geotechnical concerns related to the performance of structures located in areas of moderate to high seismicity with loose/soft soils. Over the past 30 years, much of the research focus has been to study the earthquake response of sands and relatively "clean" sandy soils, whereas the behaviour of silty sands and silts has been investigated only on a very limited scale. It has been noted that certain fine-grained soils can be as much susceptible to liquefaction as relatively clean sands, and there is a significant controversy and confusion regarding the liquefaction potential of silts including clayey silts (Seed et al. [1]). For example, Boulanger et al. [2], based on the earthquake performance of the Moss Landing site during the Loma Prieta earthquake, has noted that the commonly used Chinese Criteria (Marcuson et al. [3]) for liquefaction assessment of fine-grained soils should be applied with caution. These limitations have also been noted in an examination of laboratory cyclic triaxial and simple shear test data from seven silty soil sites in British Columbia, Canada (Atukorala et al. [4]). Although some of these uncertainties can be reduced by laboratory testing of high quality

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undisturbed samples, it must be recognized that the current practice still relies on criteria/guidelines based on simpler soil parameters, properties, and approaches for the evaluation of liquefaction potential. The recent work by National Center for Earthquake Engineering Research – NCEER (Youd et al. [5]) clearly indicates that no consensus position has yet been reached on the assessment of liquefaction potential of fine-grained soils, suggesting that more study, particularly in the form of laboratory element testing, is warranted in this regard.

Controlled laboratory studies that have been conducted to assess the liquefaction of silty soils are very few. Moreover, the main focus of the laboratory work conducted (Thevanayagam et al. [6], Polito and Martin [7], Kuerbis et al. [8]) has been on the effect of the presence of silt on a sand matrix and not primarily in understanding the response of silts and silty clays. The applicability of relevant results from some of these laboratory studies are further limited due to their sample re-constitution techniques leading to soils fabrics that are not necessarily considered representative of field conditions.

In consideration of the above background, a detailed laboratory element testing research program is currently underway at the University of British Columbia (UBC) to study the cyclic loading response of Fraser River silt originating from the Fraser River Delta in the province of British Columbia, Canada. This paper presents some of the preliminary observations from this study in relation to stress-strain response and liquefaction characteristics of silt. The results are also compared with laboratory findings from cyclic shear tests conducted to study the performance of re-constituted Fraser River sand originating from the same deltaic soil deposit.

MATERIAL TESTED AND TEST PROGRAM

The silt material for this research was obtained from a site located on the north riverbank of the South Arm of the Fraser River, at the southern foot of No. 3 Road of Richmond, B.C., Canada. The choice of this native silt as the test material for the current program was judged reasonable because of its presence in large parts of the highly populated areas of Fraser River Delta, and its likely susceptibility to liquefaction. The Fraser Delta sediments have a thickness of up to 200 m, and consist of: overbank silts extending up to 6 m in thickness, overlying up to 20 m in thickness of deltaic sands, which are underlain by a thick deposit of fine sand and clayey silts.

A piston sampler that employed specially fabricated ~75-mm diameter, 0.76-m long tubes (with no inside clearance, a 5-degree cutting edge, and 1.4 mm wall thickness) was used to obtain a number of undisturbed samples from the upper Fraser River silts. Leroueil and Hight [9] in their recent state-of-the-art paper have noted that piston sampling using thin, sharp-edged tubes offers a suitable and acceptable means of obtaining relatively undisturbed samples of fine-grained soils. The silt specimens for the tests presented herein were selected from one of the above tube samples. The sample was retrieved from a depth of 5.6 m to 6.2 m below the ground surface at the test location. This depth zone is judged to be relatively uniform based on the available data from in situ cone penetration testing (CPT testing) conducted at the site.

The samples used for this study show interbedded layers of silt of millimeter scale with some very thin (<1 mm) sandy layers. The gradation of Fraser River silt used in this study is shown in Figure 1, and the corresponding parameters derived from index testing combined with data available from in situ testing are summarized in Table 1. A microscopic view of the silt and the interbedded layers of sand are shown in Figure 2.

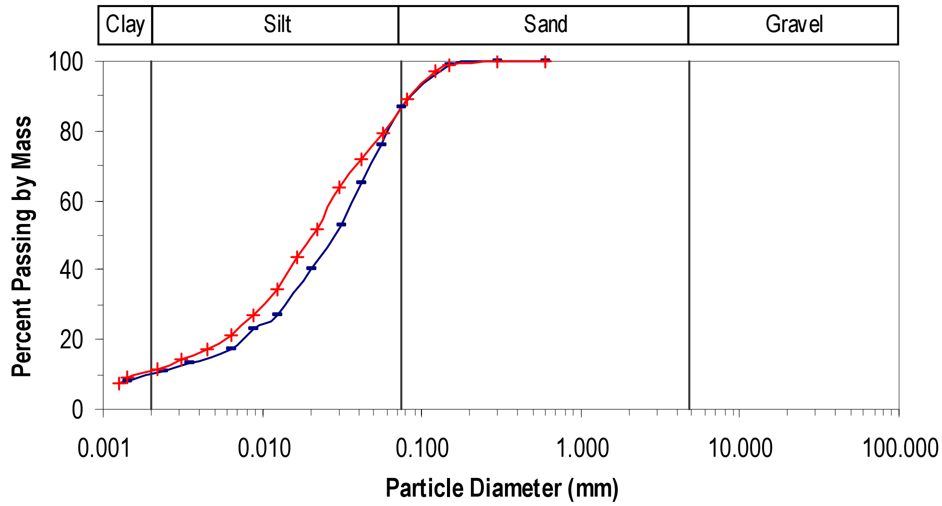
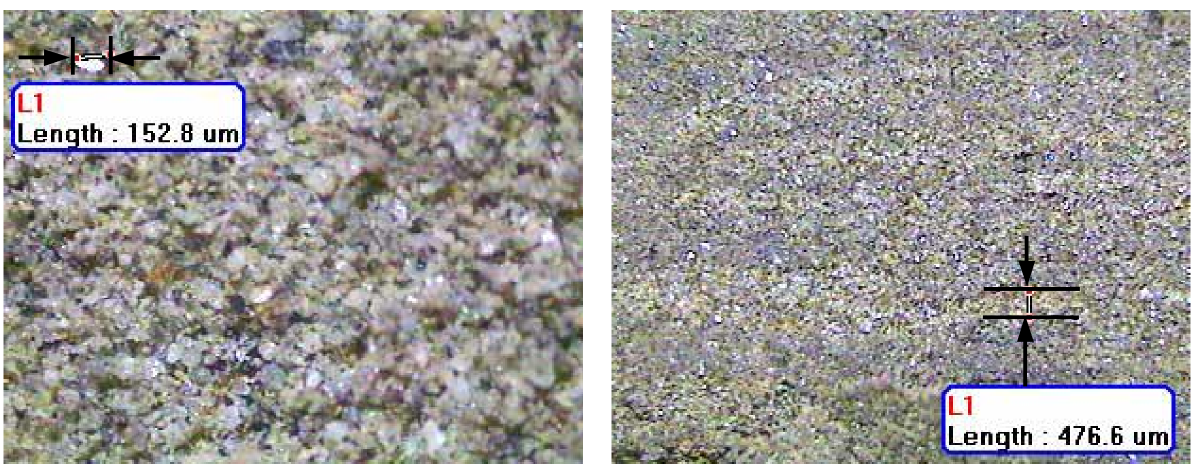


Figure 1. Grain size analysis results from two representative soil samples of Fraser River silt.

Table 1. Index parameters and in situ test data for Fraser River silt.

Index Property	Value
Water content, W(%)	37.5
Liquid limit, W_L (%)	30
Plastic limit, W_P (%)	25
Plasticity Index, I_P	5
% of particles < 0.002mm	10%
% of particles > 0.075mm	13%
Unified soil classification	ML
Specific gravity, G_s	2.69
CPT resistance, q_t (MPa)	1.2 – 1.8
Vane shear strength, S_u (kPa)	40



a. Silt particles **b. Interbedded layers of sand**

Figure 2. Microscopic view of Fraser River silt

A one-dimensional consolidation test was initially conducted to obtain an understanding of the consolidation characteristics and preconsolidation pressure for the material. The results indicated a preconsolidation pressure of 75 to 80 kPa. A constant volume monotonic simple shear test and a series of five constant volume cyclic shear tests were conducted to investigate the undrained cyclic shear response of the silt. The NGI-type (Bjerrum and Landva, [10]) cyclic direct simple shear test (DSS) device at UBC, which is considered to closely simulate seismic loading conditions, was used as the test apparatus. In constant volume DSS tests, the diameter and height of the soil sample is essentially constrained against changes while the vertical stress (load) on the sample is continuously monitored during the testing process. It has been shown that the decrease (or increase) of vertical stress in a constant volume DSS test is essentially equal to the increase (or decrease) of pore water pressure in an undrained DSS test (where the constant volume condition is maintained by not allowing the volume of pore water to change, Finn et al. [11]). The cyclic shear loading was applied at a frequency of 0.1 Hz. This consisted of a symmetrical sinusoidal pulse at constant cyclic shear stress (τ_{cy}) amplitude. A continuous record of test data was obtained using a computer interfaced data acquisition system. The test variables monitored consisted of full time-histories of horizontal shear stress (τ), decrease in vertical stress (equals induced excess pore water pressure, Δu) and horizontal shear strain (γ).

All the DSS specimens were initially consolidated to a vertical effective stress level (σ'_{vo}) of 100 kPa with no applied static shear stress (i.e. τ=0, level-ground) prior to commencement of constant volume (monotonic or cyclic) shear loading. Since this 100 kPa stress level is above the estimated preconsolidation pressure, the test results presented in this paper, clearly, would correspond to the response of the silt when in a normally consolidated stress state. Additional tests are currently being performed on specimens consolidated to stress levels that are essentially similar to, and less than, the preconsolidation pressure, and these results will be presented in a separate paper that is under preparation by the authors. While the use of these relatively higher stress levels may not allow preserving possible aging-related effects, it would mimic a consolidation state in the silt resulting from the placement of permanent fills that often take place as a part of site development works in Fraser River Delta. It was also noted that the use of a consolidation stress of 100 kPa would provide an opportunity to compare with a wide database at UBC from DSS tests on Fraser River sand that corresponds to the same consolidation stress level.

As a part of undertaking cyclic shear tests, it was recognized that a definition for the onset of liquefaction is needed to examine the response between different tests as well as to understand the behaviour in relation to existing approaches. While a selected strain level is not necessarily an appropriate measure of liquefaction, as an “index” of comparison and for certain discussion purposes, liquefaction can be considered to have triggered when the single-amplitude horizontal shear strain (γ) reaches a certain value. For the purpose of this study, liquefaction was considered to have occurred when the single-amplitude horizontal shear strain reaches 3.75% in a DSS sample, a criterion that has been used in many previous liquefaction studies at UBC. It is equivalent to reaching a 2.5% single-amplitude axial strain in a triaxial sample, which also is a definition for liquefaction previously suggested by the National Research Council of United States (NRC [12]). As may be noted later, the tests were not terminated upon reaching liquefaction as per above strain criteria; instead, they were conducted to higher horizontal shear strain (γ) levels to obtain a clear understanding of the fundamental stress strain response.

TEST RESULTS

Monotonic loading response

Figure 3 presents the stress path and stress-strain response from a constant volume, monotonic, strain-controlled DSS test on Fraser River silt consolidated to a vertical stress (σ'_{vo}) of 100 kPa (i.e. normally consolidated initial stress state). As may be noted, the sample initially deformed in a contractive manner followed by a dilative response that commenced around 5% shear strain. In terms of the stress-strain characteristics, the sample clearly exhibited a strain-hardening behaviour that is typical of materials undergoing shear-induced dilative response.

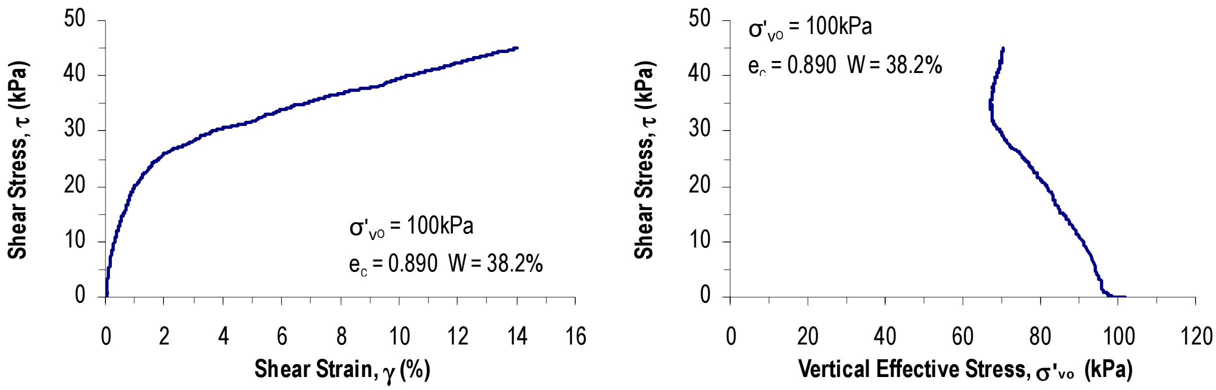


Figure 3. Stress-strain response and stress path during constant volume monotonic DSS loading of Fraser River silt

Cyclic loading response

Figures 4 and 5 show the typical stress path and stress-strain relationships of Fraser River silt during two of the cyclic DSS tests conducted with constant cyclic stress ratio [CSR = (τ_{cy}/ σ'_{vo})] amplitudes of 0.14 and 0.2, respectively. The generation of excess pore water pressure ratio with the number of cycles for all five test samples that were subjected to cyclic loading is presented in Figure 6. (Note: As discussed earlier, decrease of vertical stress in a constant volume DSS test is essentially equal to the increase of pore water pressure in an undrained DSS test).

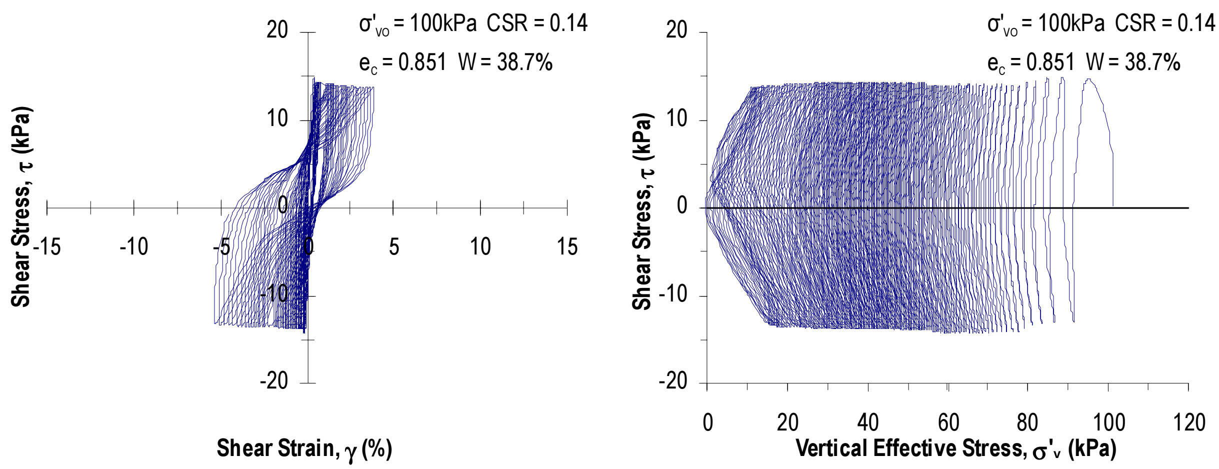


Figure 4. Stress-strain response and stress path during constant volume cyclic DSS loading of Fraser River silt; CSR=0.14.

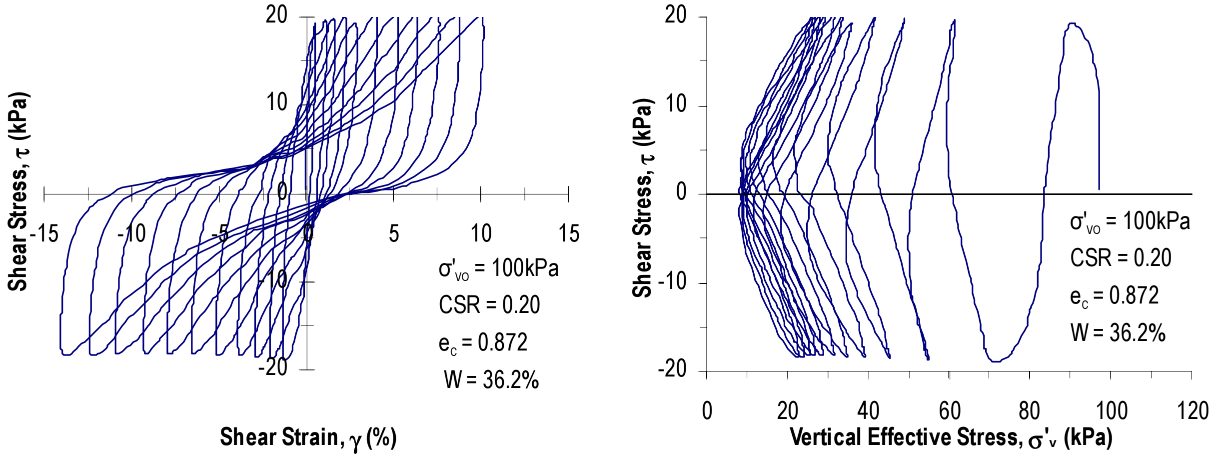


Figure 5. Stress-strain response and stress path during constant volume cyclic DSS loading of Fraser River silt; CSR=0.20.

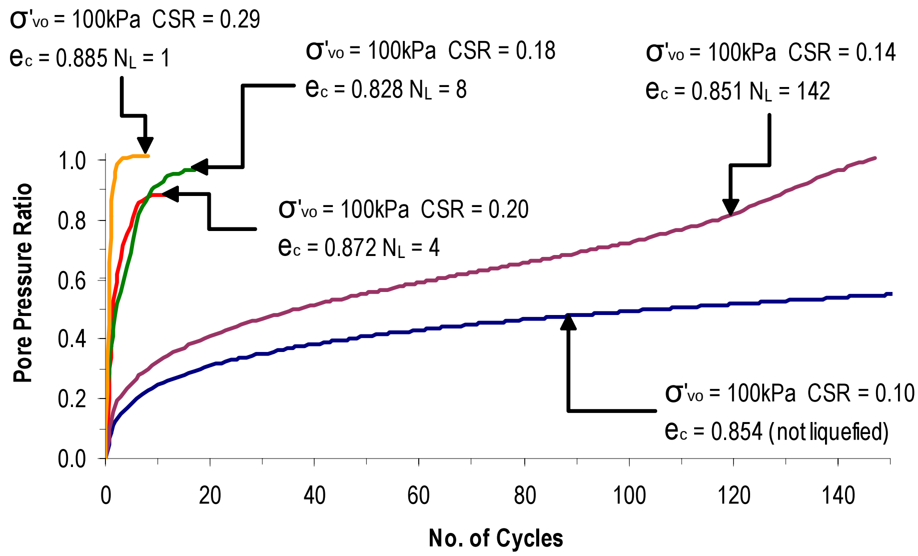


Figure 6. Pore water pressure ratio versus number of loading cycles from constant volume cyclic DSS loading of Fraser River silt.

It can be noted that the test shown in Figure 5 (having subjected to more severe cyclic loading than that for the test in Figure 4) reached liquefaction in a relatively smaller number of cycles. It is interesting to note that both the samples showed completely contractive response during both loading and unloading parts of the 1st cycle of loading. In the subsequent cycles, commencing the second cycle, the samples exhibited dilative tendency during "loading" (or increasing shear stress) and significant contractive response during "unloading" (or decreasing shear stress). This dilative tendency during "loading" quarter-cycles implies an early manifestation of phase transformation condition (Note: Phase transformation is the point at which the rate of development of excess pore water pressure changes from positive to negative). The noted significant contractive response during subsequent "unloading" quarter-cycles suggests significant "plastic unloading" that takes place in samples that have experienced phase transformation. The above behaviour of silt is very much similar in form to the cyclic shear response observed for dense reconstituted Fraser River sand when tested at a consolidation relative density D_{rc} = 80% (or void ratio e_c = 0.685) using the UBC-DSS device (Sriskandakumar [13]). It is also worth mentioning that the results reported by Wijewickreme et al. [14] from the same research program on Fraser River sand at UBC indicates a significantly contractive cyclic shear response for the loose samples of same sand (D_{rc} = 40%, e_c = 0.812). In spite of having a relatively higher void ratio (e_c = 0.87-0.88) than the loose Fraser River sand, it is evident that the undrained cyclic shear response of Fraser River silt is closer in form to the behaviour of a compact sand.

As shown in Figure 6, during cyclic loading, the cumulative excess pore water pressure ratio ($r_u=\Delta u/\sigma'_{vo}$) in the samples increased with increasing number of loading cycles. Moreover, except for the specimen that was subjected to a CSR of 0.1, all the specimens eventually experienced zero, or near zero, transient vertical effective stress conditions during cyclic loading. This is essentially the “cyclic mobility type” response that has been well observed during laboratory research on the undrained cyclic shear response of sands. The stress-strain response plots in Figures 4 and 5 clearly indicate the association of the overall reduction of shear modulus with the development of excess pore water pressure. It can be noted that the Fraser River silt experienced significantly large permanent cyclic shear strains under moderate levels of cyclic loading which is an important consideration from an engineering design/performance point of view (e.g. γ = 12 to 13% in 11 cycles of CSR = 0.2, see Figure 5).

Figure 7 shows the variation of the cyclic resistance ratio (CRR) versus number of cycles required to trigger liquefaction (N_L), on the basis of γ = 3.75% criteria as discussed earlier. The results developed from DSS tests on air-pluviated and water-pluviated Fraser River sand reported by Wijewickreme et al. [14] and Sivathayalan [15], respectively, using the same criteria are superimposed in the figure for comparison. Clearly, the Fraser River silt has a significantly higher cyclic resistance in comparison to that for Fraser River sand, although the former had a relatively larger void ratio than the latter.

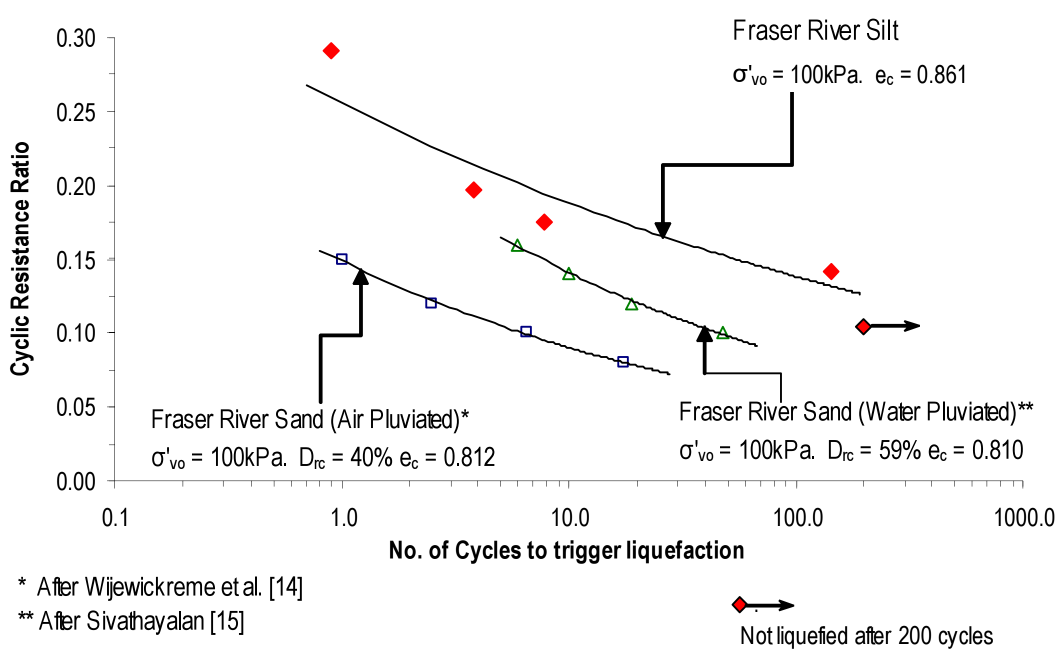


Figure 7. Cyclic resistance ratio versus number of cycles to trigger liquefaction from constant volume cyclic DSS loading of Fraser River silt.

Based on the empirical "Chinese" criteria for the evaluation of liquefaction susceptibility (Marcuson et al. [3]), the Fraser River silt tested herein in would classify as a material that should be "tested" to determine the liquefaction susceptibility (i.e. falls outside the "safe" zone in terms of this classification). More recently, based on observation of liquefied soils in Turkey during the Kocaeli earthquake, Bray et al. [16] also has proposed new criteria for the evaluation of the liquefaction susceptibility of fine-grained soils. This criterion uses the ratio of water content and liquid limit and the plasticity index as indicative parameters. The Fraser River silt of this study also classified into the category of "susceptible to liquefaction" based on Bray et al. [16] criteria. For the silt tested herein, the experimental observations from DSS testing are in line with the outcomes from the above empirical classifications.

Post-cyclic consolidation response

The settlements that occur due to dissipation of pore water pressures after an earthquake is another important consideration in assessing the performance of structures founded on liquefiable soils. In the present study, upon completion of constant volume cyclic loading, the Fraser River samples were one-dimensionally reconsolidated to their original effective vertical consolidation stress level of 100 kPa. The observed volumetric strains during post-cyclic consolidation (δ) are summarized in Table 2. As may be noted, the samples that experienced excess pore water pressure ratios (r_u) close to 100% suffered significantly high post-cyclic consolidation strains (2.4 to 4.2%) in comparison to the sample that developed relatively small r_u (~50%). The post-cyclic consolidation in the latter case was only in the order of ~0.5%. This suggests significant changes to the particle structure due to liquefaction and subsequent reconsolidation. The observed trends are generally in line with the post-cyclic consolidation behaviour observed from tests on sands.

Using the experimentally obtained 1-dimensional "static" consolidation characteristics, it was possible to determine the required "equivalent" vertical effective stress increments to cause the above levels of compression if this silt was consolidated using static loading (see Table 2). It is clear that settlements that are equivalent to those arising from a large preload thickness would materialize if the silt deposit liquefied as a result of cyclic loading.

Table 2. Volumetric strains after post-cyclic consolidation, δ compared with maximum r_u and equivalent effective confining stress to cause δ

Maximum excess pore water pressure ratio, r_u (%)	Number of tests	Volumetric Strain during post-cyclic consolidation, δ (%)		Equivalent effective confining stress required to cause δ using "static" consolidation (kPa)
50	1	0.5		140
>85	4	Minimum:	2.4	240
		Maximum:	4.2	400

CONCLUSIONS

Cyclic shear loading response of Fraser River Delta silt was investigated using the direct simple shear (DSS) device. Undisturbed samples of silt obtained using a piston sampler that employed specially fabricated thin-walled tubes, with no inside clearance and a sharp 5-degree cutting edge, were used in the testing program. During the first cycle of loading, all the tested samples exhibited complete contractive response during both increasing as well as decreasing phases of shear stress. However, during subsequent cycles, the samples exhibited dilative tendency during “loading” (or increasing shear stress) and significant contractive response during “unloading” (or decreasing shear stress). With cumulative excess pore water pressure increasing with the number of load cycles, the samples developed significant shear strains (in excess of 10%) under moderate cyclic stress ratio levels. The mechanism of strain development was noted to be cyclic mobility with zero, or near zero, transient effective stress conditions.

The observed trends of stress-strain and pore water pressure development under cyclic loading for Fraser River silt are generally similar to those previously noted for the response of dense (dilative) sands. Because of the dilative nature, normally consolidated Fraser River silt displayed a significantly higher cyclic resistance than that observed for loose Fraser River sand in spite of the relatively higher void ratio in the former than the latter. Post-cyclic consolidation tests indicated that the silt samples that experienced high excess pore water pressure ratios (i.e. r_u close to 100%) suffered significantly high post-cyclic consolidation volumetric strains (2.4% to 4.2%) in comparison to the sample that developed relatively small r_u values (~50%). This suggests significant changes to the particle structure due to liquefaction and subsequent reconsolidation.

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