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Some observations on the cyclic loading response of a natural silt

Quelques observations sur la réponse cyclique d'un silt naturel

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ABSTRACT
An experimental research program has been undertaken to study the earthquake response of silt obtained from a deltaic soil deposit. The cyclic shear response of the silt is investigated using constant volume direct simple shear (DSS) tests conducted on normally consolidated samples without initial static shear stress bias. Details of the test program and its findings in relation to the influence of cyclic pre-shearing on the mechanical response under subsequent cyclic loadings are presented. The results indicate that relatively large excess pore water pressures (or cyclic strains) induced during initial cyclic loading, and the resulting shear strains, contribute to decreasing the resistance of silt to withstand future cyclic loadings. In essence, the weakening of soil fabric that takes place due to large cyclic strains appears to override any strengthening effects resulting from the increase in density due to post-cyclic consolidation. The findings are similar to the previously observed effects of pre-shearing on the cyclic shear response of sands.

RÉSUMÉ
Un programme de recherche expérimental a été entrepris pour étudier la réponse sismique de silt obtenue à partir d'un dépôt deltaïque de sol. La réponse cyclique de cisaillement du silt est étudiée en utilisant les essais cycliques de volume constant de cisaillement direct simple. Des essais ont été effectués, sans polarisation statique initiale d'effort de cisaillement, sur des échantillons normalement consolidés. Des détails du programme d'essai et de ses résultats par rapport à l'influence du pré-cisaillement cyclique sur la réponse mécanique sous des charges cycliques subséquentes sont présentés. Les résultats des essais cycliques de cisaillement de volume constant indiquent que relativement larges pressions interstitielles (ou déformations cycliques) induites pendant le chargement cyclique initial, et les déformations résultantes de cisaillement, contribuent à diminuer la résistance du silt à de futures charges cycliques. Essentiellement, l'affaiblissement du tissu du sol qui a lieu en raison de grandes déformations cycliques semble dépasser tous les effets de renforcement résultant de l'augmentation de la densité due à la consolidation post-cyclique. Les résultats sont semblables aux effets précédemment observés du pré-cisaillement sur la réponse cyclique de cisaillement des sables.

1 INTRODUCTION

In areas of high seismic risk, potential for damage due to soil liquefaction is a major concern in engineering design, and many millions of dollars is spent on seismic design/retrofit. Silty soils are prevalent in most earthquake-prone soft-soil areas, and recent investigations have shown that certain fine-grained soils can be as much susceptible to liquefaction as relatively clean sands. There is also significant controversy and confusion with respect to the current understanding of the liquefaction potential of silts including clayey silts (Seed et al., 2001; Boulanger et al., 1998; Atukorala et al., 2000; Sanin and Wijewickreme, 2004). Although some of these uncertainties can be reduced by laboratory testing of high quality 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 (Bray et al., 2004; Andrews and Martin, 2000; Finn et al., 1994; Marcuson et al. 1990). While significant research has been conducted on sands, the seismic response of silts has not received the same emphasis (Polito and Martin, 2001; Thevanayagam and Mohan, 2000). Advancement of the fundamental understanding of the seismic response of silts, therefore, is critical to the improvement of design approaches and development of optimum design solutions (Wijewickreme and Sanin, 2004). The need for more study, particularly in the form of laboratory element testing, is further supported by the recent work by Multidisciplinary Center for Earthquake Engineering Research – MCEER (Youd et al., 2001) that indicates no consensus position on the assessment of liquefaction potential of fine-grained soils.

With the above background, a systematic laboratory research program has been undertaken at the University of British Columbia (UBC) to study the cyclic loading response of silt obtained from a natural deltaic soil deposit. This paper presents some of the details of the test program and its findings, particularly in relation to the influence of cyclic pre-shearing on the mechanical response under subsequent cyclic loadings. The cyclic shear response (i.e. pore water pressure generation and stress-strain characteristics) of the silt is explored using the direct simple shear (DSS) device.

2 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 in Richmond, B.C., Canada. This natural silt is prevalent in large parts of the highly populated areas of Fraser River Delta, and it is considered susceptible 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, 0.9-m long stainless steel 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. It has been noted that piston sampling using such thin, sharp-edged tubes offers a suitable and acceptable means of obtaining relatively undisturbed samples of fine-grained soils (Leroueil and Hight, 2003). The samples were 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.

Examination of the samples indicated 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.

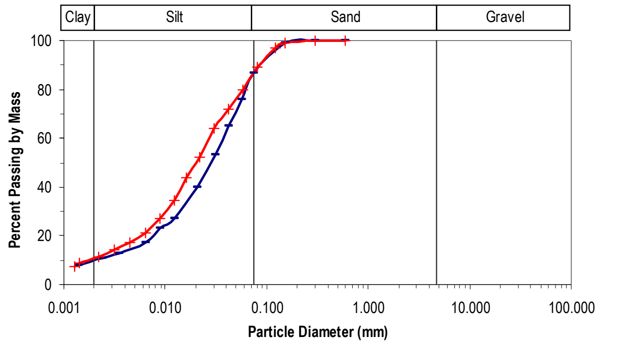


Figure 1. Grain size analysis from two representative soil samples of Fraser River Delta silt.

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

Index Property	Values
Water content, w_c (%)	37.5
Liquid limit, LL (%)	30.5
Plastic limit, PL (%)	27.3
Plasticity Index, IP	3.2
Liquidity Index, I_w	3.2
% 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

Based on one-dimensional consolidation testing, an apparent preconsolidation pressure of 75 to 80 kPa was obtained for the tested samples. A series of constant volume cyclic shear tests were conducted to investigate the undrained cyclic shear response of the silt using the NGI-type (Bjerrum and Landva, 1966) cyclic direct simple shear test (DSS) device at UBC, which is considered to closely simulate seismic loading conditions. 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 mass of pore water to change (Finn et al., 1978).

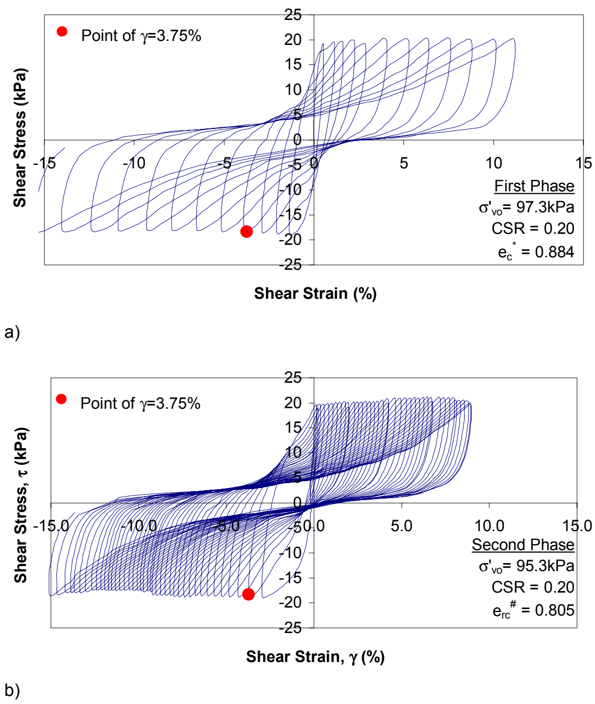
All the DSS specimens were initially consolidated to a vertical effective stress level (σ'_{vo}) of 100 kPa with no applied static shear stress (i.e. τ_{st}=0, level-ground) prior to commencement of constant volume (monotonic or cyclic) shear loading. Since this 100 kPa stress level is above the estimated preconsolidation pressure, the test results presented herein correspond to the response of the silt under a normally consolidated stress state. The cyclic shear loading was applied at a frequency of 0.1 Hz. This loading 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 (equivalent to induced excess pore water pressure, Δu) and horizontal shear strain (γ). The loading cycles were applied until horizontal cyclic shear strain amplitudes in the order of 15% were reached. Once this phase (first phase) of cyclic loading ended, the samples were then subjected to re-consolidation to the original 100 kPa stress level. At this point, the samples were subjected to another phase (second phase) of constant volume cyclic shear loading, with the applied cyclic stress ratio identical to that used in the first phase. The loading was continued until cyclic shear strain (γ) amplitudes again in the order of 15% were reached. After the second cyclic phase, the samples were re-consolidated to 100kPa, once more, while monitoring post-cyclic consolidation settlements.

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, the 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. This criterion 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, 1985).

3 TEST RESULTS

3.1 *Cyclic Loading Response*

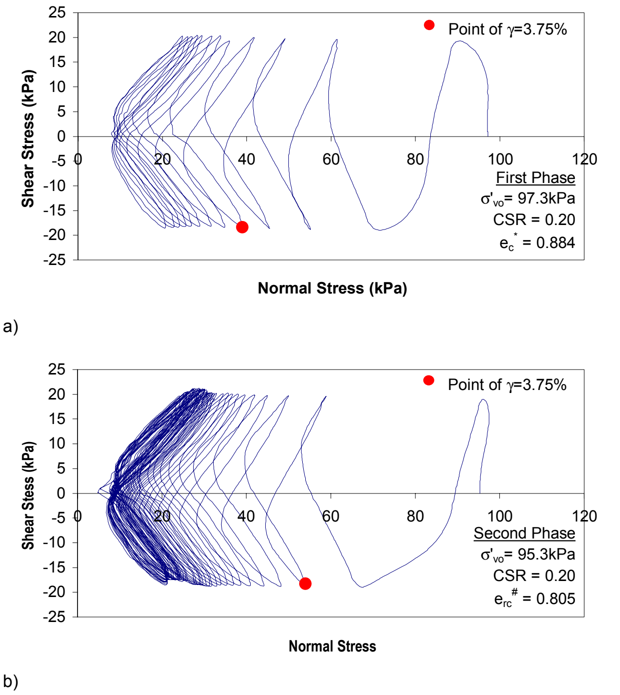
Typical stress-strain response observed under the two phases of cyclic DSS loading is compared in Figure 2. The corresponding comparison for stress paths, excess pore water pressure, and strain development with number of cycles is given in Figures 3 through 5, respectively.



*: Void ratio after consolidation (prior to first phase)

#: Void ratio after re-consolidation (after first phase - prior to second phase)

Figure 2. Stress strain response during constant volume cyclic DSS loading of Fraser River Silt. a) First cyclic loading phase, b) Second cyclic loading phase.



*: Void ratio after consolidation (prior to first phase)
#: Void ratio after re-consolidation (after first phase - prior to second phase)

Figure 3. Stress path observed during constant volume cyclic DSS loading of Fraser River Silt. a) First cyclic loading phase, b) Second cyclic loading phase.

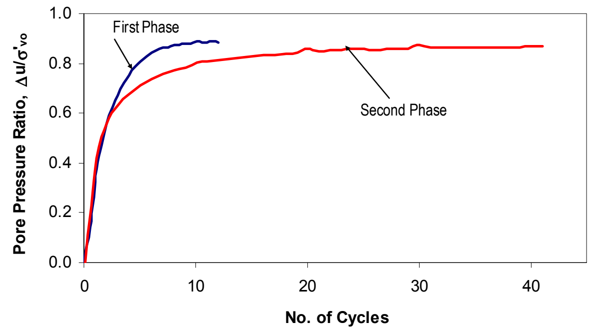
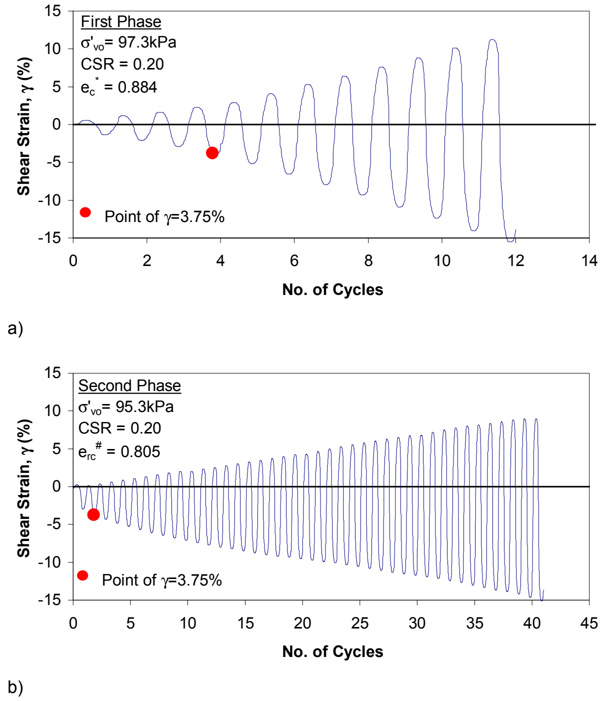


Figure 4. Maximum pore water pressure ratio vs. number of cycles during constant volume direct simple shear test on Fraser River Delta silt.

During the first cyclic phase, a completely contractive response was observed during loading and unloading parts of the 1st cycle of loading. In the subsequent cycles of the same loading phase, 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). In an overall sense, the sample experienced cumulative increase in excess pore water pressure with associated progressive degradation of shear stiffness. The observed "cyclic mobility type" stress-strain response for the silt in the first cyclic loading phase is very much similar in form to the cyclic shear response observed from DSS tests on dense reconstituted sand (Sriskandakumar 2004; Kammerer et al. 2002).

In the second cyclic loading phase, although the sample experienced a slight dilative response during the "loading" part of the 1st cycle (i.e., 1st quarter cycle), a very significant contractive response (pore water pressure development) was noted during the immediately followed "unloading" part. The resulting rapid drop in effective stress caused the sample to perform softer in comparison to the first phase. The sample reached the pre-defined liquefaction triggering strain ($\gamma = 3.75\%$) in about 1.5 cycles in the second cyclic phase in comparison to the 4 cycles that was required to reach the same γ value in the first cyclic phase. It is notable that this observed response is despite a void ratio reduction $\Delta e = 0.079$ due to consolidation at the end of first cyclic phase. The observed behaviour is in accord with the previous findings by others on the response of water-pluviated samples of sand subjected to large pre-shearing, and it is attributable to particle fabric changes in the previous shearing phase (Finn et al., 1970; Ishihara and Okada, 1982; Vaid et al., 1989).



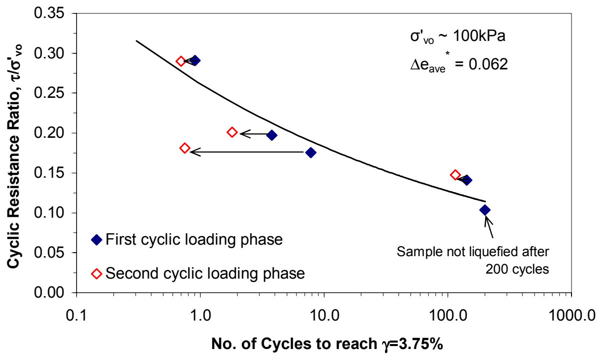
*: Void ratio after consolidation (prior to first phase)
#: Void ratio after re-consolidation (after first phase - prior to second phase)

Figure 5. Shear strain development with the number of cycles during constant volume cyclic DSS loading of Fraser River Silt. a) First cyclic loading phase, b) Second cyclic loading phase.

It can also be noted that, in the second cyclic phase, the sample begins to behave in a stiffer manner with increasing number of cycles. For example, 41 cycles were required to reach a shear strain level of $\gamma = 15\%$; this is significantly larger in comparison to 12 cycles that was required reach the same level of strain in the first cyclic loading. It appears that some strengthening in the soil fabric takes place during latter part of second cyclic phase.

Figure 6 shows the variation of the cyclic resistance ratio (CRR) versus number of cycles required to trigger liquefaction on the basis of $\gamma = 3.75\%$ criteria as discussed earlier. Closed symbols represent the first cyclic loading phase and the accompanying open symbols represent the second cyclic loading phase. Clearly, the number of cycles of loading required to achieve $\gamma = 3.75\%$ during the second cyclic phase is consistently less than first cyclic phase. It is worthwhile noting that the change in void ratio that occurred in the samples due to reconsolidation after the first cyclic loading varied between 0.046 and 0.079 with an average $\Delta e_{ave} = 0.062$. Despite the densification that occurred after the first cyclic loading phase, all the samples liquefied (reached $\gamma = 3.75\%$) in fewer cycles during the second cyclic loading phase.

As discussed by Leroueil and Hight (2003), the mechanical response of soils is controlled by many factors such as mineralogy, grain size/shape, plasticity, particle arrangement (fabric), micro-structure, packing density, confining stress level, age, etc. Figure 6 further supports the notion that the decrease in cyclic shear resistance (CRR) due to potential degradation of particle fabric, as a result of previous shearing, has overshadowed any gain in CRR that would have taken place due to reduction of void ratio during consolidation.



*: Average change in void ratio after first cyclic loading phase

Figure 6. Cyclic resistance ratio versus number of cycles to reach γ=3.75% on first and second cyclic loading phases from constant volume DSS tests on Fraser River silt.

3.2 *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) after the first and second cyclic loading phases are summarized in Table 2. As may be noted, the samples that experienced excess pore water pressure ratios ($r_u = \Delta u/\sigma'_{vo}$) close to 100% suffered significantly high post-cyclic consolidation strains (2.4 to 4.2%) in comparison to the sample that developed relatively small ru (~50%). The consolidation subsequent to second cyclic loading indicated further settlements (i.e., post-cyclic consolidation strains ~ 0.12 to 2.8%). Although these settlements are less than those observed in the 1st cyclic loading, it is clear that the potential for this additional settlement was generated purely by the cyclic shearing action imparted during the second cyclic phase.

Table 2. Volumetric strains after cyclic loading, δ, compared with maximum excess pore water pressure, r_u, during cyclic loading.

Maximum excess pore water pressure r_u (%)	Number of tests	Volumetric strain after first cyclic loading phase, δ (%)	Volumetric strain after second cyclic loading phase, δ (%)
50	1	0.5	-
>85	4	Minimum: 2.4 Maximum: 4.2	Minimum: 1.3 Maximum: 2.3

4 SUMMARY AND CONCLUSIONS

Cyclic shear loading response of Fraser River Delta silt was investigated using constant volume cyclic direct simple shear (DSS) tests. Undisturbed samples of silt were obtained using specially fabricated thin-walled tubes, with no inside clearance and a sharp 5-degree cutting edge. The effects of cyclic pre-shearing were investigated by subjecting the samples to a first cyclic loading phase followed by re-consolidation to the initial stress level and a subsequent second cyclic loading phase.

In an overall sense, during first cyclic loading phase, the samples experienced cumulative increase in excess pore water pressure with associated progressive degradation of shear stiffness. These observed trends of stress-strain and pore water pressure development for Fraser River silt are generally similar to those previously noted for the response of dense (dilative) sands.

During the subsequent (second) cyclic loading phase following re-consolidation, samples exhibited a rapid drop in effective stress (raise in pore water pressure) and performed softer than in the first cyclic loading phase. Despite the densification that took place during re-consolidation after first cyclic phase, the sampled reached the liquefaction triggering (γ = 3.75%) in a fewer number of load cycles than those required for the first phase. It appears that the decrease in cyclic shear resistance (CRR) due to degradation of particle fabric as a result of previous shearing has overshadowed any gain in CRR that would have taken place due to reduction of void ratio during consolidation.

Post-cyclic consolidation after the first cyclic loading phase 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 in comparison to the sample that developed relatively small r_u values. Although less than the observed settlements after the first cycle of loading, post-cyclic consolidation following the second cyclic phase still exhibited considerable settlements (i.e., up to 2.8%). Again, this can be considered as a reflection of extensive particle rearrangement suffered by the silt specimens during cyclic loading.

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