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CYCLIC SHEAR RESPONSE OF LOW PLASTIC FRASER RIVER SILT

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ABSTRACT

The cyclic shear response of natural low-plastic Fraser River silt was investigated using constant-volume direct simple shear (DSS) testing. The silt material displayed cumulative increase in excess pore water pressure with progressive degradation of shear stiffness (cyclic mobility type response) during constant volume cyclic shear loading, regardless of the initial effective confining stress, cyclic shear stress ratio, initial static shear stress bias, and overconsolidation ratio. The noted absence of strain-softening and/or loss of shear strength under cyclic loading suggests that the tested silt is unlikely to experience flow-failure during seismic shaking. The study provides an example that demonstrates the value of detailed laboratory studies in the assessment of liquefaction potential of low plastic silt.

Introduction

Liquefaction of saturated soils and associated geotechnical hazards are among the primary concerns related to the performance of structures located in areas of seismic activity. Fine-grained silty soils with high levels of saturation are commonly found in natural river deposits such as the Fraser River Delta of British Columbia, Canada. Silty soils also originate as a man-made waste product in tailings, derived from the processing of ore in the mining industry. The undrained response of saturated sands has been the topic of extensive research during the past thirty years, while the behaviour of fine-grained silty soils has been studied only on a very limited scale (Idriss and Boulanger 2008; Bray and Sancio 2006; Sanin and Wijewickreme 2006; Wijewickreme et al. 2005). Recent evidence of ground failure in low-plastic fine-grained soils during strong earthquakes has emphasized the need for understanding of the response of silts under cyclic loading in a more fundamental manner, and laboratory element testing plays an essential role in this regard. In spite of the above concerns, not much research has been conducted on silts, partly due to the difficulties in obtaining high quality undisturbed samples and/or in reconstituting laboratory test specimens.

A comprehensive laboratory research program has been undertaken at the University of British Columbia (UBC), Vancouver, Canada, to study the mechanical response of silts, with the primary motivation of developing a database for understanding the response of natural silts. As a part of

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this work, constant volume shear response of a natural silt was investigated using direct simple shear (DSS) testing.

This summary paper presents some key findings from the above work; in particular, the observed effects of confining stress, overconsolidation, initial static shear stress bias, and level and duration of loading on the characteristic cyclic loading response of low plastic silt are summarized. The study demonstrates that detailed laboratory studies can play a major role in assessing the liquefaction potential of sites underlain by low plastic silts.

Laboratory Testing Program

The data presented herein have been derived from constant volume cyclic direct simple shear (DSS) testing conducted at the UBC geotechnical research laboratory. The tests were performed on specimens prepared from field tube samples retrieved from natural, relatively young, uniform channel-fill silt located within the upper depth zones of the Fraser River Delta of the Province British Columbia, Canada. Cyclic DSS tests have been noted to be reasonably representative of field conditions during earthquake loading. The response of a given soil to cyclic loading is controlled by many parameters such as packing density, microstructure, fabric, level and duration of cyclic loading, confining stress, initial static bias. These parameters have been noted to primarily govern development of excess pore water pressures, stiffness, and strength in a soil mass during the occurrence of an earthquake, in turn, controlling the overall seismic response. The laboratory program at UBC was developed with these considerations in mind.

The device used for DSS testing was NGI-type (Bjerrum and Landva 1966), and it allowed the testing of a specimen having a diameter of ~70 mm and height of 20 to 25 mm. In DSS tests, as an alternative to suspending the drainage of a saturated specimen, a constant volume condition can be enforced even in a dry soil by constraining the specimen boundaries (diameter and height) against changes. The specimen diameter is constrained against horizontal strain using a steel-wire reinforced rubber membrane, and the height constraint is obtained by clamping the top and bottom loading caps against vertical movement. 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 (conducted on saturated specimens) where the near constant volume condition is maintained by not allowing the mass of pore water to change (Dyvik et al. 1987, Finn et al. 1978).

The DSS testing involved: (i) consolidating the silt specimens to a selected initial vertical effective stress (σ'_{vo}); and (ii) then subjecting the specimens to cyclic shear loading with or without applied initial static shear stress bias (i.e., simulating sloping or level ground conditions, respectively). In some cyclic tests, the initial σ'_{vo} levels were kept approximately at or above the preconsolidation stress (σ'_p) inferred from one-dimensional consolidation testing of undisturbed samples from the field (i.e., to obtain normally consolidated, NC, specimens). After initial consolidation under the applied vertical stress, some of the specimens were subjected to a static shear stress (τ_o) to meet a prescribed initial static shear stress bias ($\alpha = \tau_o/\sigma'_{vo}$). The static shear stress (τ_o) was applied in an incremental manner while keeping the specimen in a drained condition; the specimen was allowed to reach equilibrium (i.e., stability in vertical and shear strains) under a given static shear stress increment, prior to application of the subsequent static shear stress increment. Additional cyclic DSS tests were also undertaken on specimens that were initially consolidated to a target preconsolidation stress (σ'_p) and then unloaded to a vertical effective stress (σ'_{vo}) of 100 kPa, so that a desired overconsolidation ratio (OCR) was achieved prior to the application of cyclic loading. During cyclic DSS testing, symmetrical sinusoidal horizontal shear stress (τ_{cy}) pulses were applied to achieve selected levels of constant applied cyclic stress ratio [CSR = (τ_{cy}/σ'_{vo})] amplitudes, at a frequency of 0.1 Hz.

The tested Fraser River silt was obtained using fixed-piston tube sampling conducted in a conventional mud-rotary drill hole. Specially fabricated ~75-mm diameter, 0.9-m long, stainless-steel tubes (with no inside clearance, a 5-degree cutting edge, and 1.5 mm wall thickness) were used for the sampling. Based on the degree of sample disturbance assessed by measuring the void ratio changes during reconsolidation, Sanin and Wijewickreme (2006) noted that this method offered a suitable and acceptable means of obtaining good quality specimens of natural low plastic silt. The material parameters and grain size distribution of Fraser River silt are summarized in Table 1 and Figure 1, respectively. As may be noted from Table 1, the test material had a plasticity index of about four indicating a relatively low-plasticity.

Test Results and Discussion

Typical Stress Strain Response and Effect of Initial Confining Stress

The stress path (τ versus σ'_v) and stress-strain (τ versus γ) relationships obtained from constant-volume cyclic tests conducted on Fraser River silt specimens initially consolidated to σ'_{vo} ~100 kPa and ~400 kPa, under essentially similar CSR loadings, are presented in Figures 2 and 3, respectively. The stress path and stress-strain relationships obtained for a specimen initially consolidated to σ'_{vo} ~ 100 kPa, and then subjected to cyclic shear loading with a CSR amplitude of 0.29 is shown in Figure 4. For a given specimen, the void ratio after the initial consolidation phase, which is also the void ratio during cyclic loading, has been denoted by e_c in the figures.

The tested specimens initially showed predominantly contractive response, and with increasing number of load cycles, they displayed cumulative increase in excess pore water pressure with associated progressive degradation of shear stiffness. It is important to note that the shear response gradually changed from contractive to dilative (or experienced phase transformation) during the 'loading' (or increasing shear stress) phases. However, significant contractive response was noted during 'unloading' (or decreasing shear stress) phases suggesting significant unloading plastic volumetric strains in specimens that have experienced phase transformation. In a given cycle, the shear stiffness experienced its transient minimum when the applied shear stress was close to zero. All the specimens eventually experienced zero, close to zero, transient vertical effective stress conditions during cyclic loading. It is also of importance to note that the response-pattern of the two specimens (presented in Figures 2 and 3) was remarkably similar in spite of their significantly different initial consolidation confining stress levels (σ'_{vo}).

In an overall sense, 'cyclic-mobility-type' strain development was observed in all the tests conducted at different CSR levels (e.g., Figures 2 through 4). Liquefaction in the form of strain softening accompanied by loss of shear strength did not manifest in any of the tests regardless of the applied CSR value, or the level of excess pore water pressure. This suggests that the tested Fraser River silt is unlikely to experience flow failure (i.e., potential for catastrophic failure) under undrained cyclic loading. This response is generally similar in form to the constant-volume cyclic shear responses observed from cyclic shear tests on fine-grained mine tailings (Wijewickreme et al. 2005), and clays (Idriss and Boulanger 2008), and compact to dense reconstituted sand (Sriskandakumar 2004; Kammerer et al. 2002).

In order to assess the cyclic resistance of the silt, the applied CSR is plotted against number of cycles to reach single-amplitude $\gamma = 3.75\%$ ($N_\gamma = 3.75\%$) in Figure 5. This is equivalent to reaching a 2.5% single-amplitude axial strain in a triaxial specimen, which also is a definition for "liquefaction" originally suggested by the US National Research Council (NRC 1985). It is noted that the data points presented are mainly for specimens normally consolidated to confining stresses between 85 kPa (i.e., approx. in-situ stress) and 200 kPa. In addition, results from two cyclic tests conducted on specimens consolidated to $\sigma'_{vo} = 300$ kPa and 400 kPa are also superimposed. The data points seems to fall on a single trend-line suggesting that cyclic resistance is relatively insensitive to the confining pressure (and the changed initial void ratio due to consolidation) and that the response is influenced only by the applied CSR. This behaviour is in accord with the typical behavioural frameworks noted for NC clay.

It is of interest to review the above observations with respect to the generally accepted response for relatively clean sands. In sands, the cyclic resistance generally increases with increasing density; moreover, for a given relative density, the cyclic resistance in sands has been noted to decrease with increasing effective confining stress (Vaid and Sivathayalan 2000). The observations presented herein suggest that, for the tested Fraser River silt, the dilative tendency arising due to stress densification seems to have overcome the possible contractive tendency due to the increase in confining stress. Park and Byrne (2004) and Wijewickreme et al. (2005) have noted similar effects due to stress densification in sands.

Effect of Initial Static Shear Stress Bias

Typical results for the same material from a test conducted with an initial static shear stress bias are presented in Figure 6. Again, cyclic mobility type strain development was observed throughout the cyclic loading process. Strain softening or loss of shear strength did not manifest in any of the tests conducted with static bias in spite of the α value and applied CSR level, or the degree of excess pore water pressure developed. This observation further suggests that the tested silt is unlikely to experience flow failure under cyclic loading (based on tests conducted with $\alpha \leq 0.15$). Examination of the test results, however, indicated that the rates of excess pore water pressure generation and shear strain development increase with increasing value of α.

The variation of cyclic resistance ratio (CRR) versus $N_\gamma = 3.75\%$ related to data from tests conducted at different values of α, are shown in Figure 7. The CRR versus $N_\gamma = 3.75\%$ relationship for each value of α have been represented by the trend-lines as shown; the data reveals that the CRR of the tested material decreases with increasing α.

Effect of Overconsolidation

Typical stress path and stress-strain relationships obtained from constant volume cyclic shear testing of an overconsolidated specimen of Fraser River silt are presented in Figure 8. The test was conducted with CSR amplitude of 0.21, commencing from a vertical effective consolidation stress of σ'_{vo} ~ 100 kPa. Because of the relatively similar initial σ'_{vo} and CSR, the results can also be directly compared with those data from the test on normally consolidated silt shown in Figure 2. The mechanism of strain development for the OC specimen is also via cyclic mobility and, thus, similar in form to those observed for the counterpart tests conducted on NC specimens. However, in contrast to the response of normally consolidated silts (see Figures 2 through 4 and 5) that exhibited a completely contractive response during both loading and unloading parts of the 1st cycle of loading, the OC specimens seem to have manifested phase transformation from contractive to dilative almost in the first loading cycle itself.

The variation of CRR versus N_{γ}=3.75% obtained using the results from the tests on overconsolidated Fraser River silt is depicted in Figure 9. The graphs clearly show that the CRR generally increased with increasing level of overconsolidation. It is also notable that this effect only became noticeable when the material was overconsolidated to a level above OCR ~ 1.3.

Closure

Under constant volume cyclic DSS loading, low plastic Fraser River silt exhibited cumulative decrease in effective stress with increasing number of load cycles (i.e., cyclic-mobility-type strain development mechanism) regardless of the initial σ'_{vo}, initial static shear stress bias (α), OCR, and applied CSR level. No strain softening and/or loss of shear strength were observed in any of the tests. The cyclic resistance ratio (CRR) of normally consolidated Fraser River silt was not sensitive to the initial σ'_{vo} for the tested stress range. The CRR of Fraser River silt was noted to increase with increasing overconsolidation ratio (OCR). The test results also indicated that the cyclic resistance would reduce with increase in initial static shear stress bias (α).

In an overall sense, for the tested natural low plastic Fraser River silt, the potential for development of significant deformations under cyclic load appears to be the dominant concern as opposed to strain softening and/or loss of shear strength. This observation suggests that the Fraser River silt is unlikely to experience flow failure under cyclic loading.

Through detailed examination of soil behaviour, Idriss and Boulanger (2008) have suggested that an approximate dividing line between coarse-grained and fine-grained behavioural patterns (from a liquefaction point of view) can be established using soil plasticity index (PI) as a parameter. They have referred to coarse-grained soils as having “sand-like” behaviour, and fine-grained soils as having “clay-like” behaviour and recommended that a PI value of 7 be used as the demarcation between coarse and fine-grained liquefaction response. Bray and Sancio (2006) have also defined criteria to classify the behaviour of fine-grained soils, based primarily on plastic limit, liquid limit and moisture content. Using Idriss and Boulanger (2008) approach, the natural Fraser River silt tested herein, with PI ~4, would be classified as “sand-like” in current practice. On the other hand, in the present laboratory study, examination of results from specimens of NC Fraser River silt suggests a laboratory-based CRR value for Fraser River silt that is clearly higher than the CRR

= 0.075 estimated based field-based charts assuming "sand-like" behaviour. Idriss and Boulanger (2008) have cautioned that the value of PI = 7 suggested as the delineation between sand-like and clay-like behaviour is in fact a transition zone, and the liquefaction assessments may have to be adjusted on a site-specific basis if justified by the results of detailed testing. The current findings from Fraser River silt serves as an example in this regard, demonstrating how detailed laboratory testing could complement field-based approaches in the assessment of cyclic shear performance of fine-grained low plastic silts.

While empirical criteria are simple and practically attractive as screening tools, understanding of the mechanism of shear strain development is fundamental to assessing the performance of soils under cyclic loading. In this context, laboratory element testing that allows capturing the effects of most controlling parameters appears to present a prudent approach for assessing the liquefaction susceptibility of silts.

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Table 1. Physical parameters of Fraser River silt.

Physical Property	Value
Water content, W_c (%)	35 to 40
Liquid limit, LL (%)	30.4[a] (0.41)[b]
Plastic limit, PL (%)	26.3[a] (0.90)[b]
Plasticity Index, PI	4.1[a]
Unified soil classification	ML
Specific gravity, G_s	2.69
*CPT resistance, q_t (MPa)	1.2 – 1.8
*Field vane shear strength, S_u (kPa)	40
Note: a= Average value; b= Standard deviation; * = Based on past (unpublished) in situ testing data available from others.	

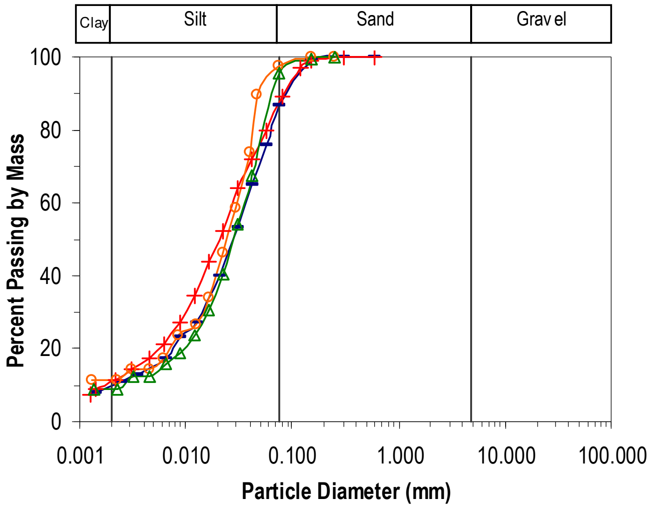

Figure 1. Typical grain size distribution of Fraser River silt.

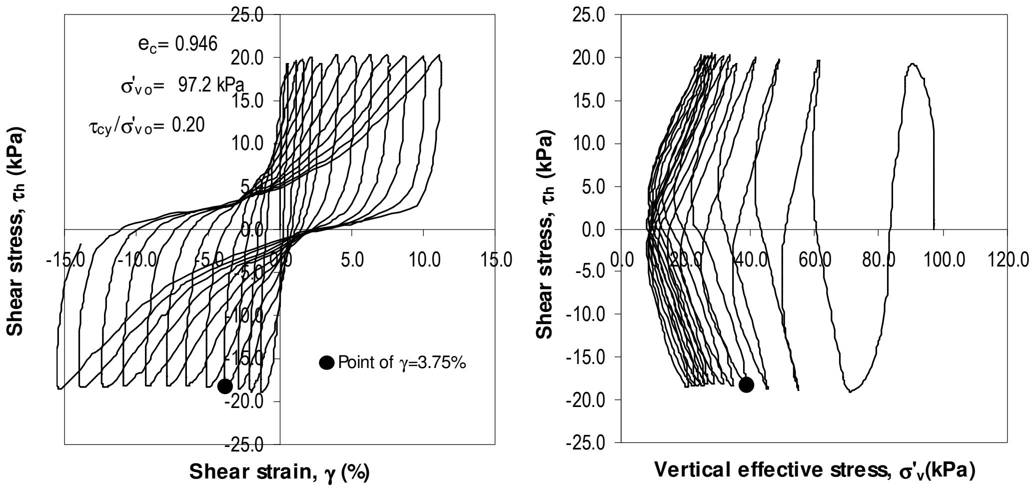

Figure 2. Stress-strain and stress-path responses of NC Fraser River silt under constant volume cyclic DSS loading (σ′vo = 97 kPa; CSR = 0.20; α = 0.0; OCR = 1.0).

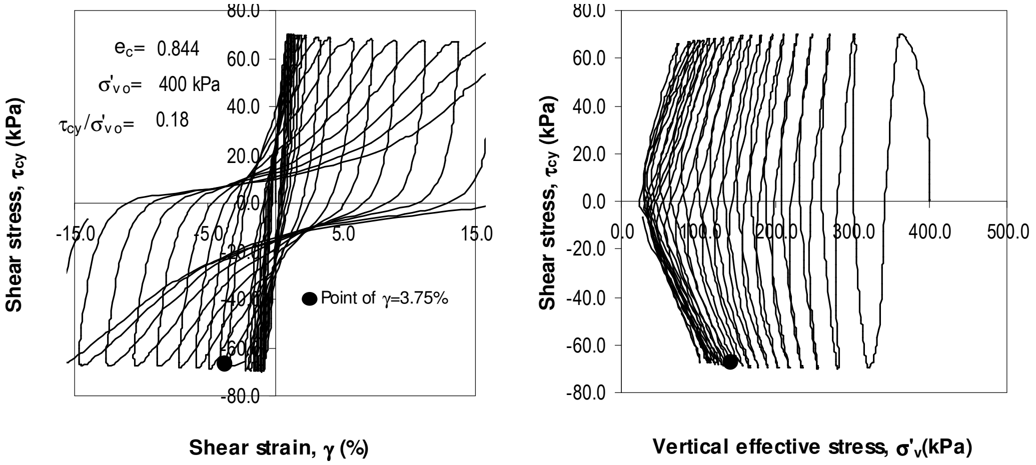

Figure 3. Stress-strain and stress-path responses of NC Fraser River silt under constant volume cyclic DSS loading (σ′vo= 400 kPa; CSR = 0.18; α = 0.0; OCR = 1.0).

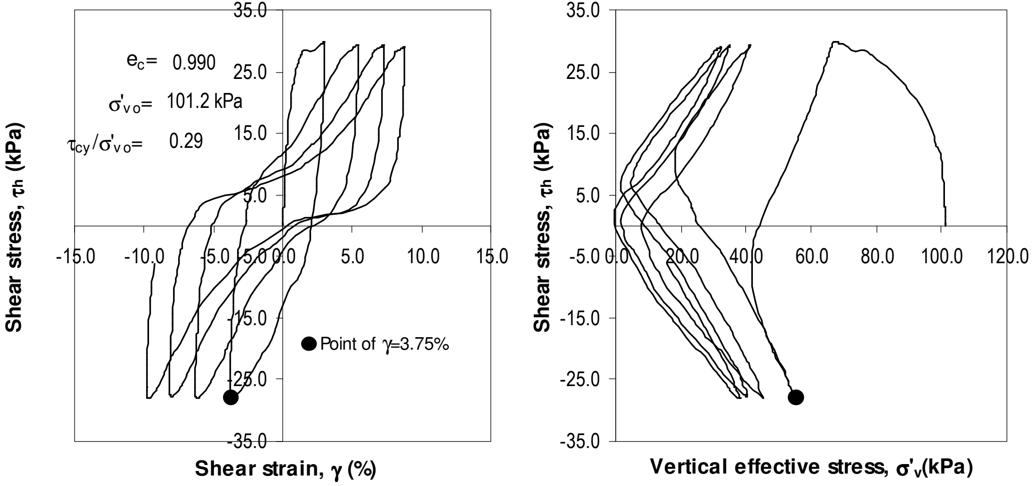

Figure 4. Stress-strain and stress-path responses of NC Fraser River silt under constant volume cyclic DSS loading (σ′vo = 101 kPa; CSR = 0.29; α = 0.0; OCR = 1.0).

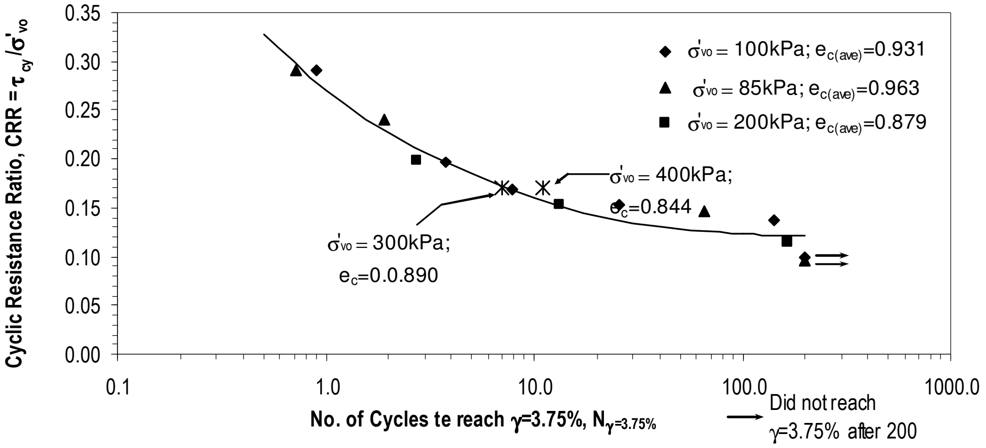

Figure 5. CRR versus number of cycles required to reach γ=3.75% from constant volume cyclic DSS tests on NC Fraser River silt (85 kPa < σ'_{vo} < 400 kPa; $\alpha = 0.0$).

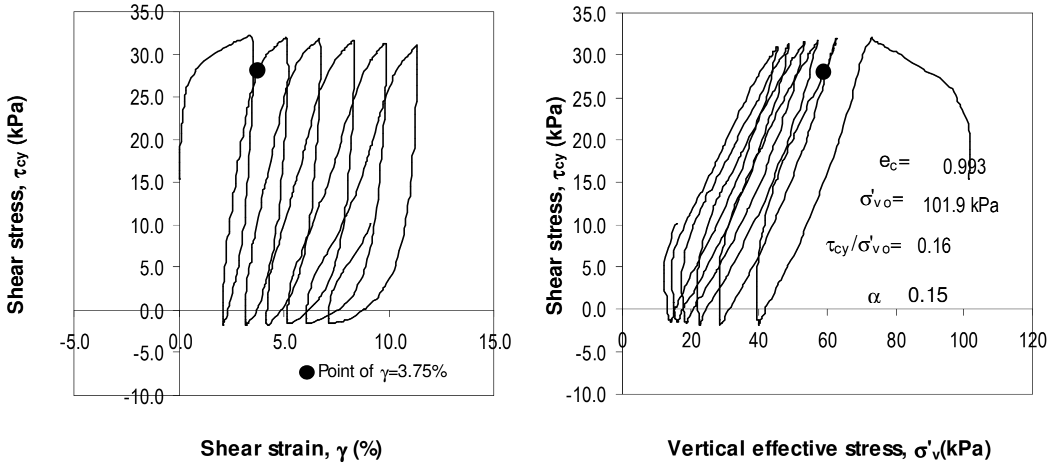

Figure 6. Stress-strain and stress-path responses of NC Fraser River silt under constant volume cyclic DSS loading (σ'_{vo} = 102 kPa; CSR = 0.16; $\alpha = 0.15$; OCR = 1.0).

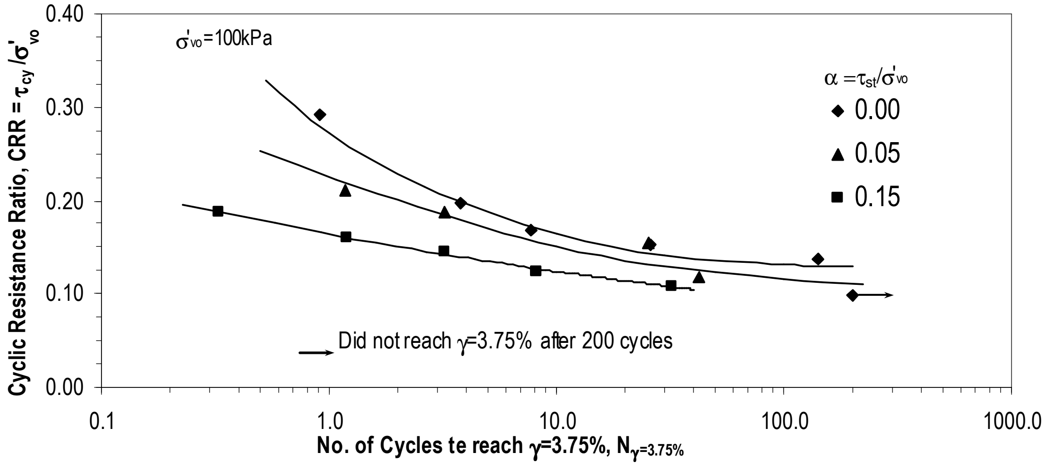

Figure 7. CRR versus number of cycles to reach γ = 3.75% from constant volume cyclic DSS tests on NC Fraser River silt conducted at different α levels (σ'_{vo}~ 100 kPa).

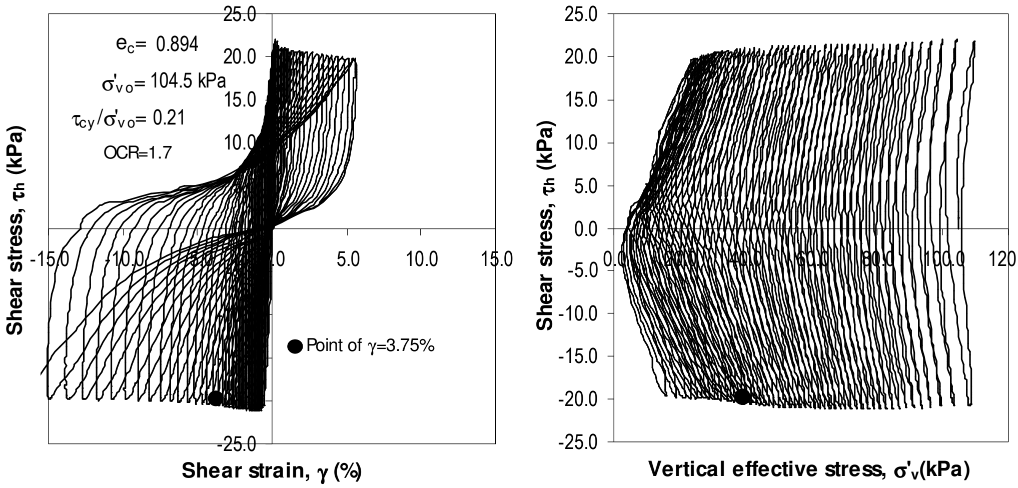

Figure 8. Stress strain curve and stress path from constant volume cyclic direct simple shear test on OC Fraser River silt (σ′$_{vo}$ = 105 kPa; CSR = 0.21; α = 0.0; OCR = 1.7).

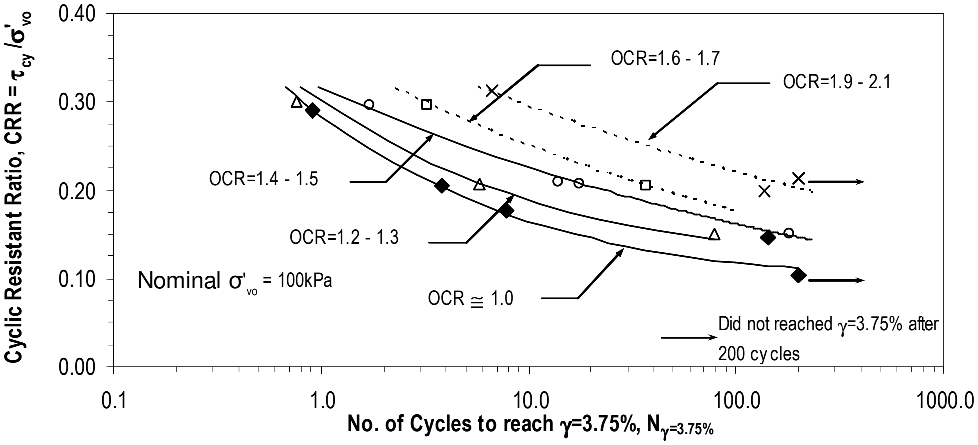

Figure 9. CRR versus number of cycles to reach γ = 3.75% from constant volume cyclic DSS tests on Fraser River silt conducted at different OCR levels (σ′$_{vo}$ ~ 100 kPa; α = 0.0).