POST-CYCLIC CONSOLIDATION RESPONSE OF A NATURAL LOW PLASTIC SILT DUE TO DISSIPATION OF CYCLIC EXCESS PORE WATER PRESSURES

D. Wijewickreme[1] and M.V. Sanin[2]

[1] *Associate Professor, Dept. of Civil Engineering, University of British Columbia, Vancouver, Canada*
[2] *PhD Candidate, Dept. of Civil Engineering, University of British Columbia, Vancouver, Canada*
Email: dwije@civil.ubc.ca, msanin@civil.ubc.ca

ABSTRACT :

The post-cyclic consolidation response of a natural low-plastic silt was examined using undisturbed silt specimens tested in a constant volume cyclic direct simple shear (DSS) device. The silt specimens initially subjected to constant volume cyclic loading at different cyclic stress ratios (CSRs), until different values of cyclic shear strain were reached, were subsequently allowed to experience one-dimensional consolidation. Post-cyclic consolidation volumetric strains ($\varepsilon_{v\text{-}ps}$) were noted to increase with the maximum pore water pressure generated during cyclic loading as well as with the maximum cyclic shear strain to which the specimens were subjected during cyclic loading. The values of $\varepsilon_{v\text{-}ps}$ correlated well with the excess pore water pressure ratio (r_u) during constant volume cyclic loading prior to consolidation.

KEYWORDS: fine-grained soils, cyclic shear response, post-cyclic consolidation, silt

1. INTRODUCTION

Saturated silty soils with high levels of saturation are commonly found in natural river deposits. Recent evidence of ground failure during strong earthquakes has indicated that certain saturated fine-grained soils can be susceptible to earthquake-induced softening and strength reduction, in turn, leading to post-cyclic settlements, foundation sliding, tilting and collapsing of structures (Bray et al. 2004; Boulanger et al. 1998). In addition to the potential loss of shear stiffness and/or strength, another key mechanism of ground deformations derives from the overall volume changes in the soil mass that take place due to the dissipation of earthquake-shear-induced excess pore water pressures. These volume changes develop in the field as post-liquefaction settlements, and they may occur both during and after earthquake shaking. The adverse impacts of these settlements on the performance of structural foundations and linear lifelines have been well documented. Typically, for level ground conditions, the amount of settlement can be computed from the volumetric reconsolidation strains induced as the excess pore water pressures dissipate.

The post-cyclic settlements in sands are generally known to be controlled by the generated pore water pressures and shear strains during cyclic loading. Due to the direct connection with pore water pressure development, the potential for volumetric strains has been often linked with the field density. Several simplified methods have been proposed to estimate probable post-cyclic settlements in sands if the field penetration resistance (i.e., standard penetration resistance (SPT) N-value or cone penetration testing (CPT) resistance) and the cyclic stress ratio (CSR) applied by the design earthquake are known (Lee and Albaisa, 1974; Tokimatsu and Seed, 1987; Ishihara and Yoshimine, 1992; Wu 2002; and Zhang et al. 2002).

Unlike for the response of sands, there is only very limited available information on the post-cyclic settlements in fine-grained soils. Yasuhara et al (2001) proposed a method based on the cyclic excess pore water pressure, plasticity index, and bearing capacity factor of safety.

Laboratory element testing has a key role in advancing the fundamental knowledge on the post-cyclic settlements. With the above background, a laboratory element testing program was conducted to study the post-cyclic consolidation characteristics of a natural silt, as a part of an overall research program to study the earthquake response of fine-grained soils, and this paper presents the findings from this experimental research.

2. MATERIALS TESTED AND TEST PROGRAM

The data presented herein are from direct simple shear (DSS) testing conducted on undisturbed low plastic silt where one-dimensionally consolidated soil specimens were initially subjected to constant volume cyclic shear loading, and then followed by post-cyclic consolidation. An NGI-type (Bjerrum and Landva 1966) DSS testing device at the University of British Columbia, Canada, was used for the test program, and the device allows the testing of a specimen having a diameter of ~70 mm and height of 20 to 25 mm. 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 near constant volume condition is maintained by not allowing the mass of pore water to change (Finn et al. 1978; Dyvik et al. 1987).

Soil originating from a relatively young, uniform surficial channel-fill silt deposit located within Fraser River Delta of the Province of British Columbia, Canada was used for the test program. The particle size distributions obtained from four silt samples from the deposit are shown in Figure 1. Some very thin (< 0.5 mm in thickness) discontinuous fine sand layers were found to be present in the silt matrix, thus, contributing to the sand content observed in the particle size distribution in Figure 1. The average parameters derived from index testing for the silt combined with some unpublished information available from past testing work by others are summarized in Table 1.

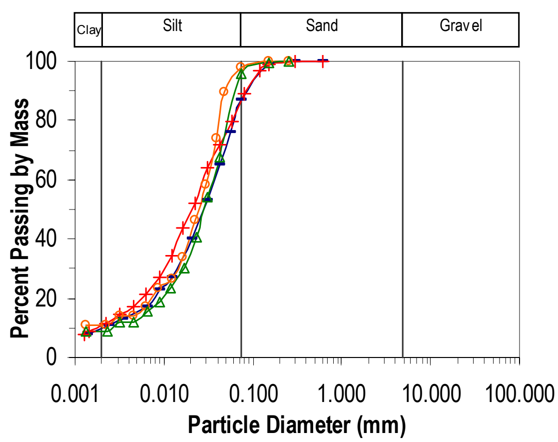

Figure 1. Grain size distribution of natural Fraser River Delta silt

Table 1. Index properties of Natural Fraser River Delta silt

Soil Property	Values
Water content, W_c (%)	34.8 to 39.6
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
Samples depth range (m)	5.50 – 8.10
Preconsolidation stress, $\sigma'_{p\text{-}1D}$ (kPa)	80 – 88[c]
*CPT resistance, q_t (MPa)	1.2 – 1.8
*Field vane shear strength, S_u (kPa)	40

Note: a= Average value; b= Standard deviation; c= From 1-D consolidation tests.
* = Based on past (unpublished) in situ testing data available from others.

Tests were conducted on specimens prepared from undisturbed Fraser River silt samples. Undisturbed samples of the silt were obtained using fixed piston tube sampling with a specially fabricated stainless steel, thin-walled tube with no inside clearance (~75 mm diameter, 5-degree cutting edge and 1.5 mm wall thickness). The use of these thin, sharp-edged tubes has been shown to offer an acceptable method to obtain good quality specimens of low-plastic Fraser River silt for laboratory testing (Sanin and Wijewickreme, 2006). After extrusion from the sample tube, the specimens of the natural undisturbed silt were secured in the DSS device with assistance from a polished-stainless steel sharpened-edge cutting-ring.

The DSS testing program is presented in Table 2. The results from a total of thirteen (13) DSS tests on undisturbed Fraser River silt were used in the present assessment, and as indicated in Table 2, the silt specimens were tested under specimens consolidated to an initial vertical effective stress of σ'_{vo} level at or above the preconsolidation stress ($\sigma'_{p\text{-}1D}$) inferred from previous one-dimensional consolidation testing on the same material (Sanin and Wijewickreme 2006). All tests were performed without initial static shear bias (i.e., simulating "level-ground" conditions). The void ratios observed for all the test specimens at the end of consolidation (e_c), just prior to constant volume cyclic loading, are also given in Table 2.

Table 2. Test program and summary of results

Test ID	e_i	OCR	σ'_{vo} (kPa)	e_c	Cyclic tests				$\varepsilon_{v\text{-}ps}$ (%)
					τ_{cy}/σ'_{vo}	$N_{(\gamma=3.75\%)}$	γ_{max} (%)	$\Delta u_r/\sigma'_{vo}$	
FRS100-010	0.991	1.0	92.4	0.921	0.10	200	0.31	0.59	0.54
FRS100-014	1.042	1.0	101.2	0.969	0.14	143	5.06	0.95	3.28
FRS100-017	0.990	1.0	101.3	0.892	0.17	8	21.45	0.92	2.43
FRS100-020	0.974	1.0	97.2	0.884	0.20	4	15.52	0.91	4.18
FRS100-029	1.041	1.0	101.1	0.990	0.29	1	7.75	1.04	3.47
FRSV100-01	1.001	1.0	100.7	0.953	0.15	N/A	1.16	0.69	0.90
FRS85-010	1.036	1.0	86.9	0.939	0.10	N/A	1.04	0.53	0.52
FRS85-015	1.017	1.0	84.9	0.945	0.15	81	15.03	0.98	4.06
FRS85-025	1.027	1.0	85.0	0.985	0.25	2	15.19	0.94	4.33
FRS85-029	1.052	1.0	87.2	0.981	0.29	1	18.98	0.91	3.63
FRS200-015	1.047	1.0	199.3	0.900	0.15	13	15.40	0.91	1.67
FRS200-020	0.989	1.0	199.8	0.855	0.20	3	18.49	0.94	4.46
FRS200-011	0.997	1.0	198.6	0.882	0.11	164	15.42	0.97	5.11

Upon completion of the consolidation phase, the specimens were subject to cyclic constant volume shear loading. Cyclic loading was applied in a stress-controlled manner at a frequency of 0.1 Hz; this consisted of a symmetrical sinusoidal pulse at constant cyclic stress ratio (CSR = τ_{cy}/σ'_{vo}) amplitude. The cyclic loading was terminated after allowing the specimens to reach different levels of shear strain; the intent, herein, was to subject specimens to post-cyclic consolidation after reaching different levels of cyclic shear distortion and maximum excess pore water pressure development. In some cases the maximum cyclic shear strain γ_{max} amplitude was ~15%, but in some others, the cyclic shearing was suspended at lower shear strain levels. This approach was adopted since, as pointed out in the introduction, the post cyclic settlements of sands are known to be affected by the maximum cyclic pore water pressure and by the maximum shear strain. After completion of the constant volume cyclic loading phase, the DSS specimens were one-dimensionally reconsolidated to their original effective consolidation stress level to assess the post-cyclic consolidation strains, the data from which were used in the assessment presented in this paper.

3. EXPERIMENTAL OBSERVATIONS

3.1 Typical cyclic shear response of low plastic silt

The shear strains and excess pore water pressures generated during cyclic loading are of direct relevance to post-cyclic consolidation settlements. The cyclic shear response of the tested Fraser River silt considered herein has already been documented in detail by the authors (Sanin and Wijewickreme 2006; Wijewickreme and Sanin 2007; Wijewickreme and Sanin 2008). However, it was decided to briefly present below typical observations on cyclic shear response of the test material since this information was judged necessary to provide the background for the assessment of post-cyclic consolidation strains, which is the main objective of this paper.

Typical stress strain and stress path response of constant volume cyclic DSS tests on undisturbed Fraser River Delta silt, performed at a selected CSR loading amplitude of 0.20 is shown in Figure 2. It can be noted that the specimen exhibit gradual increase in excess pore water pressure and degradation of shear stiffness with increasing number of load cycles. Typically, the shear stiffness experienced its transient minimum when the applied shear stress is close to zero. This "cyclic mobility type" response is generally similar in form to the undrained (constant-volume) cyclic shear responses observed from cyclic shear tests on fine-grained mine tailings, and clays, and compact to dense reconstituted sand (Wijewickreme et al. 2005; Zergoun and Vaid 1994; Wijewickreme and Sanin 2004; Sriskandakumar 2004). Liquefaction in the form of strain softening accompanied by loss of shear strength did not manifest regardless of the applied cyclic stress ratio, or the level of induced excess pore water pressure, suggesting that the silt is unlikely to experience flow failure under cyclic loading.

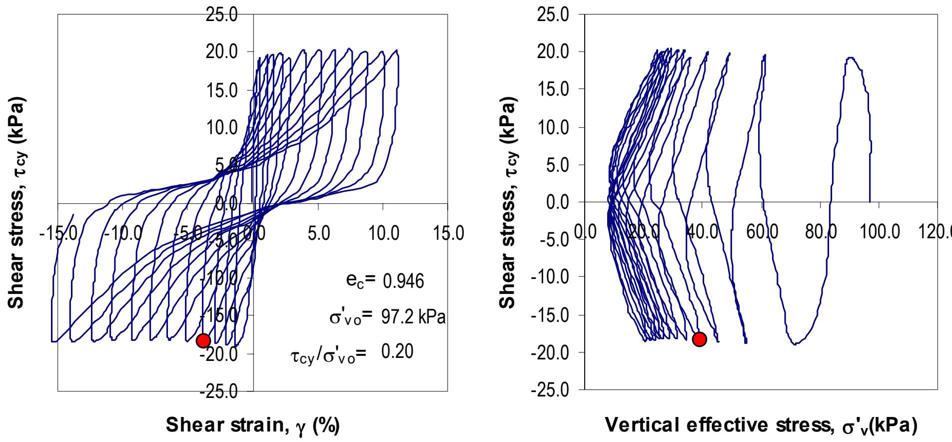

Figure 2. Constant volume cyclic DSS response of Fraser River Silt at CSR = 0.20.

The variation of excess pore water pressure ratio ($r_u = \Delta u/\sigma'_{vo}$) vs. number of loading cycles for some selected tests are given in Figure 3 to illustrate the observed trends. While all the specimens exhibit gradual increase of Δu with increasing number of loading cycles, the rate of generation of r_u with number of cycles increases with increasing applied CSR. For example, the specimen that was subjected to CSR = 0.29 developed r_u = 100% in about 4 cycles, whereas, the specimen tested with CSR = 0.10 only developed r_u = 50% even after experiencing 140 cycles of loading.

3.2 Post-cyclic consolidation response

3.2.1 Time versus post-cyclic volumetric strain characteristics

Typical volumetric (or vertical) strains observed during post-cyclic consolidation (ε_{v-ps}) of undisturbed Fraser River silt are shown in Figure 4 (since the consolidation process is one-dimensional, the terms volumetric strains and vertical strains are synonymous in a DSS device). The three curves shown in Figure 4 correspond to post-cyclic consolidation tests conducted on undisturbed soil specimens that have reached different levels of maximum cyclic excess pore water pressure ratio ($r_u = \Delta u / \sigma'_{vo}$). The time durations for completion of primary consolidation shown in Figure 4 observed for undisturbed Fraser River silt specimens were also noted to be similar to those observed during the initial consolidation phase of the same specimens prior to cyclic loading; this suggests that the coefficient of consolidation (C_v) of undisturbed Fraser River silt during the dissipation of post-cyclic excess pore water pressure is not significantly affected by the level of the level of r_u generated due to cyclic loading.

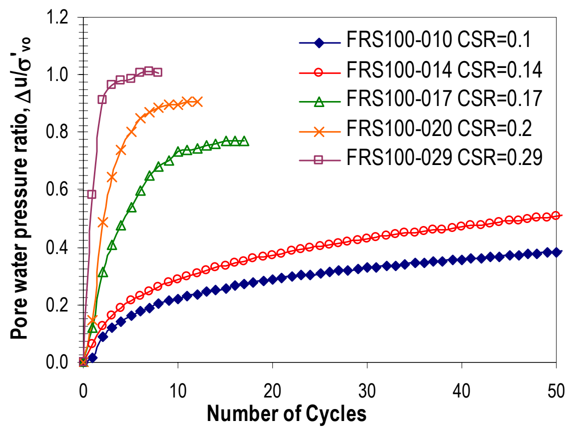

Figure 3. Excess pore water pressure ratio during constant volume cyclic DSS testing of Fraser River silt.

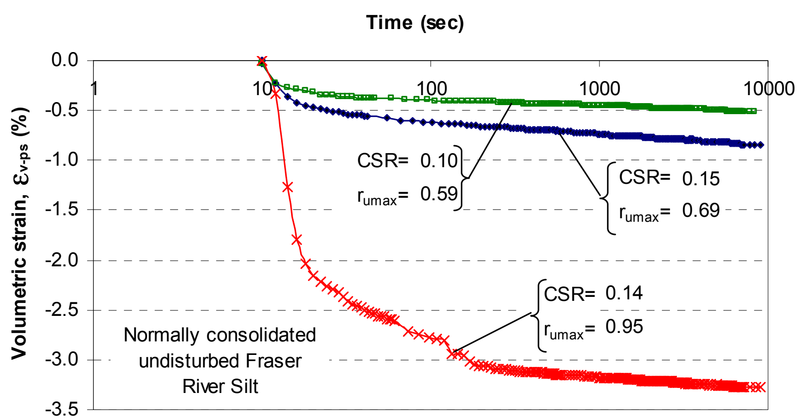

Figure 4. Typical post cyclic volumetric strain following cyclic loading of Fraser River silt.

3.2.2 Dependence of post-cyclic volumetric strains on cyclic excess pore water pressure and cyclic shear strain

Typical time versus post-cyclic volumetric strain ($\varepsilon_{v\text{-}ps}$) characteristics presented in Figure 4 for undisturbed Fraser River silt suggest that the level of maximum excess pore water pressure during cyclic loading (i.e., the level of r_u) has a significant influence on $\varepsilon_{v\text{-}ps}$ (i.e., post-cyclic consolidation settlements). The correspondence between $\varepsilon_{v\text{-}ps}$ and maximum excess pore water pressure ratio (r_u) obtained from all the tests conducted on normally consolidated undisturbed Fraser River silt specimens are presented in Figure 5. The value of $\varepsilon_{v\text{-}ps}$ seems to gradually increase with increasing r_u during cyclic loading up to an r_u value of ~0.8; in the specimens that developed relatively small r_u (<0.5), the observed post-cyclic volumetric strains were only in the order of ~0.5%. Beyond the r_u levels of 0.8, $\varepsilon_{v\text{-}pc}$ values increase rapidly where $\varepsilon_{v\text{-}ps}$ can reach values anywhere between

1.5 to 5%. In general, it can be expressed that those specimens that generated high excess pore water pressure ratios suffered significantly higher post-cyclic consolidation strains; in spite of the scatter at larger r_u values, it reasonable to say that ε_{v-ps} values correlate well with r_u.

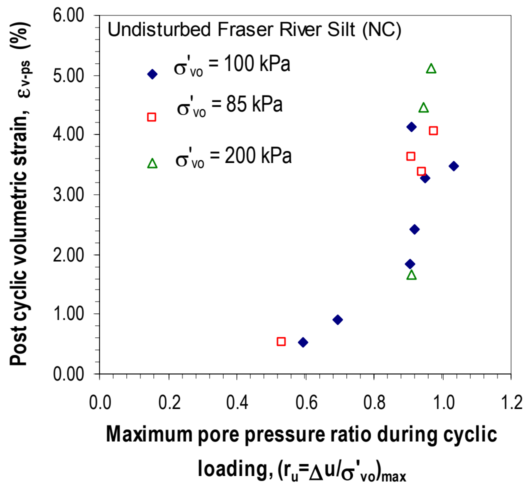

Figure 5. Post-cyclic consolidation settlements versus maximum excess pore water pressure ratio developed during constant volume cyclic DSS loading.

The noted volume changes are a reflection of significant changes in the particle fabric associated with large shear strains experienced by the specimens under relatively low effective stress conditions during previous cyclic loading. With this consideration in mind, the correspondence between ε_{v-ps} and maximum shear strain (γ_{max}) observed during cyclic loading from the same tests are examined in Figure 6. While high post-cyclic volumetric strains appear to associate with high shear strain levels from a general point of view, there seems to be a significant scatter between ε_{v-ps} versus γ_{max} compared to the correspondence observed between ε_{v-ps} and r_u in Figure 5.

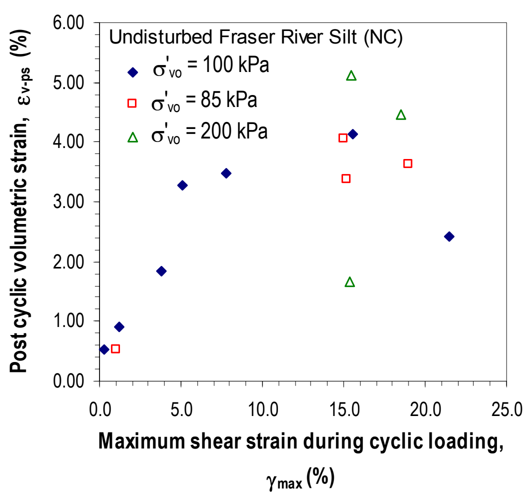

Figure 6. Post-cyclic consolidation settlements versus maximum cyclic shear strain developed during constant volume cyclic DSS loading.

4. SUMMARY AND DISCUSSION

The post-cyclic consolidation response of natural low-plastic Fraser River silt was examined using constant volume cyclic direct simple shear (DSS) followed by post-cyclic consolidation testing. The intent was to evaluate the post-cyclic consolidation volume changes experienced by silt specimens subjected to cyclic loading at different cyclic stress ratios (CSRs) and different values of cyclic shear strain. The tests were conducted on normally consolidated specimens derived from relatively undisturbed silt samples.

With respect to constant volume cyclic DSS loading, undisturbed Fraser River silt exhibited cumulative decrease in effective stress (or increase in excess pore water pressure) with increasing number of load cycles, associated with progressive degradation of shear stiffness. This observed cyclic mobility type stress-strain response is conceptually in accord with the responses previously observed on a number of natural silts (Wijewickreme and Sanin 2007).

Consolidation tests conducted on specimens initially subjected to constant volume cyclic loading indicate that post-cyclic volumetric strains ($\varepsilon_{v\text{-}ps}$) increase with the maximum excess pore water pressure ratio (r_u) generated during cyclic loading as well as with the maximum cyclic shear strain (γ_{max}) to which the specimens were subjected during cyclic loading. In spite of the scatter at larger r_u values, $\varepsilon_{v\text{-}ps}$ values correlated well with r_u; however, there was relatively significant scatter between $\varepsilon_{v\text{-}ps}$ versus γ_{max}.

ACKNOWLEDGMENTS

The data analysis presented herein was supported by research funding from the Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

Bjerrum, L., and Landva, A. (1966). Direct simple-shear tests on a Norwegian quick clay. *Geotechnique*, **16(1),** 1-20.

Boulanger, R. W., Meyers, M. W., Mejia, L. H., and Idriss, I. M. (1998). Behavior of a fine-grained soil during the Loma Prieta earthquake. *Canadian Geotechnical Journal*, **35(1)**, 146-158.

Bray, J. D., Sancio, R. B., Riemer, M. F., and Durgunoglu, T. (2004). Liquefaction susceptibility of fine-grained soils. *Proceedings of the 11th International Conference on Soil Dynamics and Earthquake Engineering and 3rd International Conference on Earthquake Geotechnical Engineering*, Berkeley, CA, 7–9.

Dyvik, R., Berre, T., Lacasse, S., and Raadim, B. (1987). Comparison of truly undrained and constant volume direct simple shear tests. **Geotechnique**, *37(1)*, 3-10.

Finn, W. D. L., Vaid, Y. P., and Bhatia, S. K. (1978). Constant volume simple shear testing. *Proceedings of the 2nd International Conference on Microzonation for Safer Construction—Research and Application*, San Francisco, CA, 839–851.

Ishihara, K., and Yoshimine, M. (1992). Evaluation of settlements in sand deposits following liquefaction during earthquakes. *Soils and Foundations*, **32(1)**, 173-188.

Lee, K. L., and Albaisa, A. (1974). Earthquake Induced Settlements in Saturated Sands. *Journal of the Geotechnical Engineering Division*, **100(GT4)**, 387-406.

Sanin, M. V., and Wijewickreme, D. (2006). Cyclic shear response of channel-fill Fraser River Delta *Soil Dynamics and Earthquake Engineering*, **26(9)**, 854-869.

Sriskandakumar, S. (2004). Cyclic loading response of Fraser River sand for validation of numerical models simulating centrifuge tests. PhD thesis, MASc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, .

Tokimatsu, K., and Seed, B. H. (1987). Evaluation of Settlements due to Earthquake Shaking. *J.Geotech.Eng*., **113(8)**, 861-878.

Wijewickreme, D., and Sanin, M. V. (2008). Cyclic shear response of undisturbed and reconstituted low-plastic Fraser River silt. *Geotechnical Earthquake Engineering and Soil Dynamics IV*. May 18-22, 2008, Sacramento, CA, ASCE, 10 pages.

Wijewickreme, D., and Sanin, M. V. (2007). Effect of Plasticity on the Laboratory Cyclic Shear Response of Fine-grained Soils. *Fourth International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, Greece.

Wijewickreme, D., and Sanin, M. V. (2006). New sample holder for the preparation of undisturbed fine-grained soil specimens for laboratory element testing. *Geotech Test J*, **29(3)**, 242-249.

Wijewickreme, D., and Sanin, M. V. (2004). Cyclic Shear Loading Response of Fraser River Delta Silt. *13th World Conference on Earthquake Engineering. Vancouver*, BC, Canada, 10 Pages.

Wijewickreme, D., Sriskandakumar, S., and Byrne, P. (2005). Cyclic loading response of loose air-pluviated Fraser River sand for validation of numerical models simulating centrifuge tests. *Canadian Geotechnical Journal*, **42(2)**, 550-561.

Wu, J. (2002). Liquefaction triggering and post-liquefaction deformation of Monterey 0/30 sand under unidirectional cyclic simple shear loading. PhD thesis, University of California, Berkeley.

Yasuhara, K., Murakami, S., Toyota, N., and Hyde, A. F. L. (2001). Settlements in fine-grained solids under cyclic loading. *Soils and Foundations*, **41(6)**, 25-36.

Zergoun, M., and Vaid, Y. P. (1994). Effective stress response of clay to undrained cyclic loading. *Canadian Geotechnical Journal*, **31(5)**, 714-727.

Zhang, G., Robertson, P. K., and Brachman, R. W. I. (2002). Estimating liquefaction-induced ground settlements from CPT for level ground. *Canadian Geotechnical Journal*, **39(5)**, 1168-1180.