Cyclic shear response of undisturbed and reconstituted Fraser River Silt

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ABSTRACT

The cyclic shear response of natural low-plastic Fraser River silt was investigated under constant volume direct simple shear loading using specimens from undisturbed samples and by reconstitution of the same material. During monotonic shear loading, the reconstituted specimens exhibited a generally weaker stress-strain response compared to those displayed by the undisturbed specimens. The results of the cyclic tests also demonstrate that the specimens of undisturbed silt, despite having a looser density under identical consolidation stress conditions, exhibited more dilative response and larger shear resistance compared to those displayed by reconstituted specimens. These observed differences between the undisturbed and reconstituted materials suggest that commonly used state variables e and σ'_{v} alone are not sufficient to determine the shear behaviour of low plasticity silt. The differences in the behaviour can be attributed to the difference in particle structure (soil fabric) between the undisturbed and reconstituted specimens.

PRESENTACIONES TÉCNICAS

La respuesta de limos de baja plasticidad provenientes del Río Fraser fué investigada en pruebas de corte simple directo a volúmen constante usando muestras inalteradas y reconstituidas del mismo material. Durante las pruebas monotónicas, los especímines reconstituidos presentaron una relación esfuerzo-deformación más baja que la de las muestras inalteradas. Los resultados de las pruebas cíclicas también mostraron que las muestras inalteradas, a pesar de tener una densidad más baja a condiciones similares de consolidación, presentaron una respuesta más dilatante y una resistencia cíclica mayor comparada con la de los expecímes reconstituídos. Estas diferencias sugieren que las variables de estado comunmente usadas e y σ'_v , no son suficientes para determinar la respuesta de limos de baja plasticidad. El contraste en la respuesta puede ser atribuido a las diferencias en la estructura de las partículas (textura) entre los especímenes inalterados y reconstituídos.

1 INTRODUCTION

Fine-grained silty soils with high levels of saturation are commonly found as natural deposits and also originate as a man-made waste product in tailings derived from the processing of ore in the mining industry. Evidence of ground failure in fine-grained soils during strong earthquakes has suggested that certain saturated low plastic fine-grained soils can be as much susceptible to earthquake-induced softening and strength reduction as relatively clean sands (Boulanger et al. 1998; Boulanger and Idriss 2006; Bray and Sancio 2006). Although wideranging studies have been undertaken to understand the performance of sands over the past 40 years, the available published information on the undrained shear response of fine-grained soils with respect to cyclic loading is limited (Polito and Martin 2001; Bray and Sancio 2006; Sanin and Wijewickreme 2006; Wijewickreme et al. 2005a). In particular, there is a need to understand the response of low plastic silts in a more fundamental manner, and laboratory testing plays an important role in this regard.

In general, it is fair to state that the behaviour of a given field soil condition is best examined in the laboratory by testing of good quality "undisturbed" soil specimens. The possibility to obtain reasonably undisturbed samples of certain low-plastic silts has been already demonstrated (e.g., Bray et al. 2004, Sanin and Wijewickreme 2006); in

spite of this, due to increased costs and difficulties with such undisturbed field sampling, there is a tendency to use reconstituted specimens for assessing the shear response of silts. Moreover, argument has also been made that the testing of reconstituted samples would be suitable if the objective is to determine the material characteristics at critical state (Jefferies and Been, 2006).

The mechanical response of soils is dependent on a including particle factors multitude of fabric. microstructure, density, and age. As pointed out by Leroueil and Hight (2003), testing of undisturbed samples of soils is critically important in representing soil conditions in-situ, and, in turn, in understanding the field response of natural soils. Significant differences in the response of soils have been observed between undisturbed and reconstituted samples of sands (Vaid et al. 1999) and silt and sandy silt (Høeg et al., 2000). These differences are mainly attributed to the differences in fabric between the undisturbed and reconstituted specimens.

For these reasons, it was considered suitable to compare the shear performance observed in undisturbed specimens of Fraser River silt with that from reconstituted material. This paper presents the results of a series of tests performed on reconstituted specimens of Fraser River Delta silt; the results are then compared to those performed with the same testing parameters on undisturbed samples. Data presented by Wijewickreme and Sanin (2008) is included along with new testing to enhance the database.

2 EXPERIMENTAL ASPECTS

2.1 Material tested

A channel-fill silt obtained from the Fraser River Delta of British Columbia, Canada, was selected for the investigation of the cyclic response of silts. The choice of silt from this area is considered relevant since it is located in one of the most seismically active regions in Canada (NBCC, 1995) and the area is experiencing rapid urban and industrial growth. The general ground surface elevation in the area is below the high-tide level; as such, the area is now protected by dikes. In addition, deltaic silts are compressible and susceptible to settlements under building loads (Crawford and Morrison, 1996).

The subject site for the present testing program is located immediately north of the South Arm of the Fraser River, on the river dyke at the southern foot of No. 3 Road in Richmond, B.C. A channel-fill silt deposit is overlain by about 3.5 m thickness of dyke-fill materials at the site. Available data from in-situ cone penetration testing, CPT, suggested that the upper part of this channel fill silt between depths of 5.6 m and 9.3 m below the ground surface is relatively uniform, and, therefore, this deposit was considered suitable as the source of test material for the present study.

A fixed-piston tube sampling conducted in a conventional mud-rotary drill hole was used to obtain a number of undisturbed samples from the silt deposit (from the same horizon identified above). A specially fabricated ~75-mm diameter, 0.9-m long tubes (with no inside clearance, a 5-degree cutting edge, and 1.5 mm wall thickness) were used for this purpose. As noted by Leroueil and Hight (2003), piston sampling using thin, sharp-edged tubes offers a suitable and acceptable means of obtaining relatively undisturbed samples of finegrained soils. Sanin and Wijewickreme (2006) assessed the quality of the specimens using Lunne et al. (1997) criteria. Based on research on uniform marine clays, Lunne et al. (1997) proposed that the normalized void ratio change $(\Delta e/e_0)$ can be used as an index of describing sample disturbance, where $\Delta e = change$ in void ratio of a laboratory specimen during reconsolidation to in situ effective stress and e_0 = initial void ratio of the specimen. This criterion suggests that samples could be considered "good to fair" in terms of sample disturbance if $\Delta e/e_0 \leq 0.07$, and the specimens are to be classified as "poor" if $\Delta e/e_0$ exceeds this value. As noted by Sanin and Wijewickreme (2006), the Fraser River silt samples obtained as per above were found to be at "good to fair" level of sample disturbance as per Lunne et al. (1997) classification indicating that the sampling and specimen preparation methods used in the present study are reasonable, and suitable for the intended laboratory research work.

Figure 1 shows the gradation curves for several samples obtained from the silt deposit. As may be noted, these generally homogeneous samples have an average clay content of 10% and sand content of 13%.

Parameters obtained from index tests are presented in Table 1. These observations also confirm the uniformity of the deposit previously noted based on field cone penetration test data.



Figure 1. Grain size analysis of different samples of Fraser River silt.

Table 1. Index parameters of Fraser River delta silt

Soil Property	Values
Depth range below ground surface	5.60 to 8.7 m
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, Pl	4.1 ^a (—1.3) ^b
Unified soil classification	ML
Specific gravity, G _s	2.69
Estimated range of effective overburden	80 – 85 kPa
stress in situ	
*CPT cone penetration resistance, qt	1.2 – 1.8 MPa
* CPT friction sleeve resistance, f _s	0.006 – 0.012MPa
*Field vane shear strength, S _u	40 kPa
Preconsolidation stress **	85 – 95 kPa

Note: a= Average value; b= Standard deviation; * = Based on past (unpublished) in situ testing data available from others; ** Data from Sanin (2005)

The reconstituted specimens were formed from a saturated slurry as follows. The material was mixed with de-aired water and left under vacuum for about 24 hours. The samples, while under vacuum were stirred occasionally to minimize entrapped air bubbles to obtain a saturated homogeneous slurry. Each sample was then transferred to a 500-mm beaker, where it was left to consolidate under its own weight for about 24 hours. The clear water accumulated at the top was removed and the remaining material was carefully stirred. Moisture content was measured at this time and the slurry was spooned to the DSS mould. The DSS test specimens were secured with o-rings and loaded to the desired vertical effective stress in an incremental manner to avoid any loss of material due to squeezing.

The slurry deposition method does not allow varying the density of the specimen to match that of the undisturbed specimens. Other methods, as the modified moist tamping technique, have been developed to change and target specific densities within the reconstituted specimen (Bradshaw and Baxter 2007). The slurry deposition method for sample reconstitution as described above was selected for the present study since it is considered to better mimic the in-situ natural deposition of the silt in a river environment.

2.2 Testing apparatus

The experimental data reported herein have been primarily derived from direct simple shear (DSS) testing where one-dimensionally consolidated soil specimens were initially subjected to monotonic or cyclic constant volume shearing. An NGI-type (Bjerrum and Landva 1966) DSS testing device at the University of British Columbia, Canada, was used for the testing program, and the device allows the testing of a specimen having a diameter of ~70 mm and height of 20 to 25 mm. The details related to the device are described in Sanin (2010). The DSS has been considered more effective than other devices in simulating effects of earthquake loading.

In the DSS device, the specimen diameter is constrained against lateral strain using a steel-wire reinforced rubber membrane. As required, a constant volume condition can be enforced by clamping the top and bottom loading platens of the specimen against vertical movement, thus imposing a height constraint in addition to the lateral restraint from the steel-wire membrane. This is an alternative to the commonly used approach of maintaining constant volume by suspending the drainage of a saturated specimen. 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 excess 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.

The DSS specimens were initially consolidated to a target consolidation stress (σ'_{vc}) at or above the in situ stress level (Sanin and Wijewickreme 2006). The reconstituted specimens were normally consolidated, commencing from an approximate zero stress (thick slurry) state to reach the target stress level. All specimens, after application of the final vertical stress, were left for consolidation for a period of 24 hours prior to commencement of shearing. All tests presented herein were performed without initial static shear bias (i.e., simulating "level-ground" conditions).

Upon completion of the initial consolidation phase, the specimens (both undisturbed and reconstituted) were subject to constant volume monotonic or cyclic shear loading as desired. 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.

Table 2 presents a summary of the testing program included in this study. The end-of-consolidation void ratios (e_c) observed for the reconstituted specimens were noted to be somewhat lower than those of the undisturbed specimens under similar consolidation stress levels (i.e., density of specimens obtained using reconstitution was observed to be higher than that of undisturbed specimens).

Table 2. Testing program and summary results

		•	σ' _{vc}	•	Cyclic tests	
		ei	(kPa)	ec	τ_{cy}/σ'_{vc}	N _(γ=3.75%)
Undisturbed	FRN-100-M	1.096	101.9	1.018		
	FRN-200-M	1.068	199.6	0.949	MONOTONIC	
	FRN-300-M	1.097	296.4	0.885		
	FRS100-010	0.991	92.4	0.921	0.10	N/A
	FRS100-014	1.042	101.2	0.969	0.14	143
	FRS100-017	0.990	101.3	0.892	0.17	8
	FRS100-020	0.974	97.2	0.884	0.20	4
	FRS100-029	1.041	101.1	0.990	0.29	1
	FRN100-016	1.029	99.0	0.942	0.15	26
Reconstituted	FRR-100-M	1.275	104.6	0.842		
	FRR-200-M	1.377	199.0	0.809	MONOTONIC	
	FRR-300-M	1.208	300.6	0.761		
	FRR100-015	1.492	97.3	0.853	0.14	3
	FRR100-010	1.470	103.4	0.866	0.10	29
	FRR100-0125	1.251	96.8	0.852	0.12	9

3 MONOTONIC RESPONSE OF UNDISTURBED AND RECONSTITUTED SPECIMENS

The stress-strain and stress path response observed from a series of constant volume, monotonic, strain-controlled DSS tests on undisturbed and reconstituted specimens of Fraser River silt initially consolidated to $\sigma'_{vc} \sim 100, 200$ and 300 kPa are presented in Figures 2 and 3, respectively.



Figure 2. Constant volume monotonic DSS test on reconstituted and undisturbed specimens of Fraser River Delta silt at varying confining stress levels: Stress-strain curves; σ'_{vc} = 100, 200 and 300 kPa.

The test results indicate that the undisturbed specimens have deformed initially in a contractive manner followed by a dilative response. The points at which phase transformation (from contractive to dilative) occurs are indicated by a "dot" symbol in Figure 3. Phase transformation seems to have occurred at the same mobilized shear stress ratio (τ/σ'_{vc}) . In terms of the

stress-strain characteristics, all the undisturbed specimens can be considered to have exhibited behaviour of no "strain-softening".



Figure 3. Constant volume monotonic DSS test on reconstituted and undisturbed specimens of Fraser River Delta silt at varying confining stress levels: Stress path curves; $\sigma'_{vc} = 100$, 200, and 300 kPa.

Except for the initial shear strain levels (say up to \sim 1%) where the behaviours were almost identical, reconstituted specimens exhibited a response more contractive than that observed for the undisturbed specimens. Moreover, the reconstituted specimens experienced a mild strain-softening response. In contrast, all the undisturbed specimens exhibited increasing shear resistance with increasing strain. In an overall sense, the reconstituted specimens, despite having a slightly lower void ratio, exhibited a weaker stress-strain response than displayed by the undisturbed specimens.

Similar observations have also been made by Høeg et al. (2002) in their comparisons between undisturbed and reconstituted specimens of natural silts and fine-grained tailings. They reported substantial differences in the stress-strain-strength behaviour of undisturbed and reconstituted specimens of these materials. In their research, all the undisturbed specimens showed dilative behaviour compared to contractive behaviour of the reconstituted specimens. As observed in this study, the densities of the reconstituted specimens analyzed by Høeg et al. (2002) were also higher than the undisturbed specimens, but they all showed lower peak strength and strain softening.

The consolidation stress state in terms of void ratio (e) and corresponding effective stress (σ'_v) are commonly considered as suitable variables to represent the state of a soil. As such, from a fundamental soil behaviour point of view, it is of interest to assess the $e-\sigma'_v$ state of the material after consolidation as well as after reaching relatively large strain levels. It is to be noted that, while the vertical effective stress (σ'_v) would change with shearinduced pore water pressure, the void ratio (e) does not change during the shearing process since monotonic DSS tests were conducted at constant volume. With this thinking, the location of $e_{c^-} \log \sigma'_{vc}$ state of the specimens for undisturbed and reconstituted specimens of Fraser River silt immediately after initial consolidation are plotted in Figure 4 using two types of open symbols. Examination of this figure reveals that initial consolidation state of undisturbed Fraser River silt follow a linear e – log σ'_{v} relationship. In a similar manner, the initial consolidation state of the reconstituted material also seems to follow a linear $e - \log \sigma'_v$ relationship, but different from that noted for the undisturbed Fraser River silt. The observed linearity is in accord with the well known behaviour for normally consolidated fine-grained soils (Atkinson and Bransby 1978). It is reasonable to state that the difference in particle fabric, aging effects, would be the cause for the difference between the normal consolidation lines for the undisturbed and reconstituted soils.



Figure 4. e-log σ'_v relationships for undisturbed and reconstituted specimens of Fraser River silt immediately after initial consolidation compared with those after reaching 15% shear strain in monotonic direct simple shear.

The e- σ'_v states of all the specimens after reaching a shear strain of ~15% are also superimposed in Figure 4 using solid symbols. For each of the undisturbed and reconstituted specimens tested, the e - log σ'_v states of the specimens after reaching a shear strain of about 15% appear to follow a straight line; these straight lines seem to align generally parallel to the counterpart e_c - log σ'_{vc} line depicting the initial consolidation response (i.e., data points with open symbols).

The e - log σ'_v states of the specimens after reaching a shear strain of 15%, under identical simple shear loading mode, are distinctly different for the undisturbed and reconstituted silt specimens. It is of relevance to examine these lines drawn at 15% strain level in relation to the well-established critical state concepts (Atkinson and Bransby 1978). If there exists a unique critical state for the tested silt, it would be logical/reasonable to deduce that: (i) the e - log σ'_{v} state of the undisturbed specimens has clearly not reached the critical state after experiencing shear strains in the order of 15%; and (ii) the e - log σ'_{v} state of the remoulded specimens after experiencing shear strains in the order of 15% would be more close in location to the potentially existent critical state than the state of the undisturbed specimens after experiencing shear strains in the order of 15%. The large strain e - log σ'_{v} state reached through monotonic shear testing of remoulded silts has been proposed as a reasonable way to determine the critical state line for silts, which in turn has been argued to be useful for developing the baseline framework especially for the assessment of static liquefaction (Jefferies and Shuttle 2002). However, the observations presented in Figure 4 would suggest that the determination of the "true" critical state line through laboratory monotonic shear testing of undisturbed silt would be extremely difficult, if not impossible. In turn, these observations also suggest that the use of a critical state e - log σ'_v line generated based on reconstituted silt specimens to assess the field performance (i.e., performance of undisturbed soil) may not be suitable for fine-grained soils.

In an overall sense, the experimental observations presented herein, with respect to the e - log σ'_v domain, suggest that the reconstituted and undisturbed silt specimens have exhibited significantly different monotonic loading characteristics, in spite of their identical mineralogical origin and grain size. These differences suggest that the commonly used variables e and σ'_{v} alone are not sufficient to define/determine the shear behaviour of low plasticity silt; the differences can be reasonably attributed to considerations such as the difference in particle structure (soil fabric) and the age that may not essentially be reflected in the void ratio. For example, the natural fabric and aging effects of the undisturbed silt would not be present in the specimens of reconstituted silt that were prepared from a slurry state; in turn, this seems to have led to a particle structure that is relatively weak in terms of its ability to offer shear resistance. These deductions are in accord with the observations made by Leroueil and Hight (2003) with respect to the performance of several other natural soils.

4 CYCLIC SHEAR RESPONSE OF UNDISTURBED AND RECONSTITUTED SPECIMENS

The results from undisturbed and reconstituted specimens of Fraser River delta silt subjected to cyclic direct simple shear loading were compared with those observed from the undisturbed specimens under identical loading (see Table 2). All the tests were conducted at nominal initial effective confining stress of 100 kPa to provide a basis for comparison between tests. Typical stress-strain and stress paths curves of tests conducted on undisturbed and reconstituted specimens are presented in Figures 5 and 6 respectively.

In a general sense, both undisturbed and reconstituted specimens seem to 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, clays, and specimens of dense reconstituted sand (Wijewickreme et al. 2005a, 2005b). In spite of the observed similarity of the strain development mechanism, there is a dramatic difference in the cyclic shear behaviour between undisturbed and reconstituted specimens under identical CSR amplitudes.





The response observed specifically at first and last loading cycles from these tests are superimposed in Figure 7 to make a direct comparison. The undisturbed and reconstituted specimens displayed completely contractive response during the 1st half cycle of loading. Beyond that point, the results for the undisturbed specimen shown in Figure 7 exhibited dilative tendency during "loading" (or increasing shear stress and contractive response during "unloading" (or decreasing shear stress). In contrast, the reconstituted specimen continued to develop excess pore water pressures at a much faster rate (i.e., perform in a contractive manner) leading to a rapid degradation of shear stiffness with increasing number of cycles – particularly, in comparison to those of the undisturbed specimen.

In summary, after being subjected to the same number of cycles at the same CSR, the reconstituted specimens seem to clearly experience accumulation of shear strain and excess pore water pressure, as well as degradation of shear stiffness in a more rapid manner (with increasing number of cycles) compared to those observed from tests conducted on undisturbed specimens. It is important to highlight that these observations are in accord with those findings for the undisturbed and reconstituted specimens from monotonic shear tests; once again, the observations reinforce the significant influence of natural fabric and aging effects on the shear response of silt.



Figure 6. Constant volume cyclic DSS test on reconstituted Fraser River Delta silt. $\sigma'_{vc} = 100 \text{ kPa}$, CSR = 0.14.

The cyclic resistance ratio (CRR) derived from the above testing can be examined by comparing the response observed from DSS testing under different applied cyclic loadings. The cyclic resistance ratio [CRR = (τ_{cy}/σ'_{vc})] versus number of cycles to reach single-amplitude $\gamma = 3.75\%$ derived from the tests conducted on undisturbed and reconstituted specimens of Fraser River silt, with different cyclic load amplitudes, are plotted in Figure 8. Despite having a comparatively higher density (see Table 2), again, it is evident that all reconstituted specimens consistently exhibited a significantly lower CRR versus number of cycles characteristic in comparison to the undisturbed specimens.

5 SUMMARY AND CONCLUSIONS

The constant volume monotonic and cyclic shear response of low-plastic, normally consolidated finegrained undisturbed and reconstituted silt Fraser River silt was examined using data from DSS tests. The intent was to compare the shear response of the reconstituted specimens with those obtained from undisturbed specimens of the same material under similar consolidation stress conditions.



Figure 7. Comparison of constant volume cyclic simple shear DSS test on reconstituted and undisturbed specimens of normally consolidated Fraser River Delta silt. First and fourth loading cycles: Stress strain and stress path curves; $\sigma'_{vc} = 100 \text{ kPa}$; CSR = 0.14.



Figure 8. Cyclic resistance ratio from constant volume cyclic DSS tests on undisturbed and reconstituted specimens of normally consolidated Fraser River Delta silt: Nominal initial effective confining stress $\sigma'_{vc} = 100 \text{kPa}$.

For the initial vertical effective confining pressure range of 100 to 300 kPa investigated using monotonic shear tests, the specimens of reconstituted low plastic Fraser River silt (despite having a lower density under identical consolidation stress conditions) exhibited a consistently more contractive volume change tendency compared to that observed from the specimens of undisturbed material consolidated to the same stress level. In an overall sense, it can be concluded that the reconstituted specimens exhibited a generally weaker stress-strain response than those displayed by the undisturbed specimens.

The consolidation stress state in terms of void ratio (e) and corresponding effective stress (σ'_v) are commonly considered as suitable variables to represent the state of a soil. However, the experimental observations presented herein, with respect to the e - log σ'_v domain, suggest that the reconstituted and undisturbed silt specimens have exhibited significantly different monotonic shear characteristics, in spite of their identical mineralogical origin and grain size. The observations also reveal that the use of a critical state e - log σ'_v line generated based on reconstituted silt specimens to assess the field performance (i.e., performance of undisturbed soil) may not be suitable for fine-grained soil.

Under cyclic loading, although cyclic mobility type response similar to undisturbed silts was noted, the reconstituted specimens seem to exhibit a more rapid excess pore water pressure generation and shear stiffness degradation with respect to increasing number of cycles. These observations are in accord with those findings for the undisturbed and reconstituted specimens from monotonic shear tests, thus, emphasizing the significant influence of natural fabric and aging effects on the shear response of silt.

These observed differences between the undisturbed and reconstituted materials suggest that commonly used variables such as e and σ'_v alone are not sufficient to define/determine the shear behaviour of low plasticity silt; the differences can be reasonably attributed to considerations such as the difference in particle structure (soil fabric) and the age which may not be reflected in the void ratio.

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