Simple shear loading response of undisturbed and reconstituted silt

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ABSTRACT
The mechanical behavior of relatively undisturbed low plastic natural silt was investigated using monotonic and cyclic constant-volume direct simple shear testing for comparison with that derived from reconstituted specimens prepared from the same material. Natural silt, retrieved from a deltaic deposit located within the Lower Mainland of British Columbia, Canada were used for the study. Reconstituted specimens were prepared using a method of slurry deposition. During monotonic shear loading, reconstituted specimens exhibited slightly higher shear strength than that of undisturbed specimens. In cyclic direct simple shear tests, all reconstituted specimens displayed higher rate of strain accumulation and pore-water pressure development compared to those observed for relatively undisturbed specimens. It appears that the combination of competing effects arising from void ratio and particle structure contribute to the shear behaviour observed at a given confining stress.

RÉSUMÉ
Le comportement mécanique de faible relativement intact limon naturel plastique a été étudiée en utilisant l'essai de cisaillement simple directe à volume constant et monotone cyclique pour la comparaison avec ceux provenant d'échantillons reconstitués préparés à partir du même matériau. Limon naturel, extrait d'un gisement de deltaïque situé dans le Lower Mainland de la Colombie-Britannique, Canada ont été utilisés pour l'étude. Les échantillons reconstitués ont été préparés en utilisant un procédé de dépôt de suspension. Pendant monotone charge de cisaillement, spécimens reconstitués présentaient légèrement plus élevé résistance au cisaillement que celle des spécimens intacts. Dans les tests cycliques de cisaillement simple directs, tous les spécimens reconstitués affichés taux d'accumulation de déformation et le développement de la pression d'eau interstitielle par rapport à ceux observés pour les spécimens relativement intacts supérieur. Il semble que la combinaison des effets opposés résultant des taux de vide et la structure des particules contribue au comportement observé cisaillement à une contrainte de confinement donnée.

1 INTRODUCTION

Laboratory element tests play a key role in understanding the fundamental load-deformation behaviour of soil in geotechnical engineering. Laboratory testing in this regard is commonly conducted with the aid of equipment such as triaxial and direct simple shear (DSS) devices on specimens prepared from high quality relatively undisturbed soil samples, or by reconstitution of bulk soil samples.

Although the testing of soil directly obtained from the field would be ideal, the inherent variability of natural soils, the disturbance and destructuration that occur due to changes in stress state during sampling pose significant challenges in obtaining high quality test samples that could meaningfully represent field soil conditions; for example, studies undertaken on fine-grained soils by many researchers serve testimony to these difficulties as well as the strong need to consider them in soil characterization (e.g., Ladd & Degroot, 2003; Santagata & Germaine, 2002; Wijewickreme & Sanin, 2006; Zapata-Medina etal., 2014).

Considering the limitations and difficulties identified above, the testing of reconstituted specimens is often considered as an alternative way to assess the stress-strain-strength characteristics particularly in fundamental research work. It has been argued that different types of reconstituted methods can be used to closely represent the soil particle structure in real-life soil deposits such as deltaic soil deposits, man-made embankments, and mine tailings storage impoundments.

The mechanical response of soil under loading depends on several factors such as confining stress, void ratio (density), age, degree of saturation and drainage conditions, including particle structure/fabric, microstructure (Leroueil et al. 1979). Oda (1972) and Leroueil & Hight (2003) have emphasized the significant influence of soil fabric/microstructure on the mechanical response. For example, the mechanical behavioural characteristics observed from specimens prepared from relatively undisturbed soil samples have been noted to be significantly different from those observed from soil reconstituted from the same material, and such dissimilarities have been attributed to the differences of soil fabric/microstructure.

Currently, a comprehensive laboratory research program is underway at the University of British Columbia (UBC), Canada, to study the behaviour of fine-grained soils under earthquake loading. In support of this work, and considering the background provided in the previous paragraph, it was considered appropriate to compare the shear behavioral characteristics of relatively undisturbed fine-grained soils with that obtained for the reconstituted specimens prepared from the same fine-grained soils.

In this regard, a series of monotonic and cyclic DSS tests were tests were performed on natural, relatively undisturbed low-plastic fine-grained soil samples, retrieved using thin-walled steel tube sampling, from a deltaic deposit located within the Lower Mainland of British Columbia (BC). Another series of tests were conducted on specimens reconstituted from the same material using a slurry deposition method. In this paper, the observed shear loading response of relatively undisturbed and reconstituted silt during monotonic and cyclic DSS tests are presented and comparisons between the two responses are made as appropriate.

2 EXPERIMENTAL ASPECTS

2.1 Material Tested

The subject site of the study presented herein is located beside the southern bank of the Nicolmekl River at 160th Street Surrey, BC, and it is within the past river floodplain of Nicomekl River (Armstrong & Hicock, 1980). Specially fabricated stainless-steel tubes (having an outer diameter of 76.2 mm, no inside clearance, with a sharpened 5-degree cutting edge, and 1.4-mm wall thickness) were used to retrieve relatively undisturbed soil samples from a test hole put down using conventional mud-rotary drilling. The water table at the location was about 1.2 m. Samples retrieved from the depth levels of 4.0 m to 5.5 m were used for the laboratory testing program. The sample disturbance was assessed according to Lunne et al. (2006) criteria which describes the sample quality based on $\Delta e/e_0$ ratio where Δe = the observed change in void ratio (of a soil specimen obtained from a given sampling process) when the specimen is reconsolidated in laboratory one-dimensional consolidation to the estimated field vertical effective stress, and e_0 = estimated void ratio of the soil under field vertical effective stress condition. The criteria suggests that the specimens could be considered 'good to fair' in terms of sample disturbance if $\Delta e/e_0$ (normalized void ratio) ≤ 0.07, and the specimens are to be classified as 'poor' if $\Delta e/e_0$ is greater than 0.07. The $\Delta e/e_0$ values derived from the 1-dimensioinal consolidation tests for the silt specimen tested herein were less than 0.07, indicating sampling quality of 'good to fair'.

Specific gravity of the silt was determined as 2.77; the plasticity index was about 7, and Index properties of the tested soil are listed in Table 1. Grain size distribution results of the silts obtained from different depth levels are presented in Figure 1.

Table 1. Index properties of the tested soil

Parameter	Value
Water content %	37~41
Specific gravity (G_s)	2.77
Plastic limit %	31~37
Liquid limit %	38~45
Plasticity index	6~8
Unified soil classification	ML
Depth level (m)	4 ~5.5
Pre-consolidation stress (kPa)	35~45

As seen from Figure 1, the soil comprises silt with a sand and clay contents of about 20% and 30%, respectively. The tested soil can be classified as silt with sand (ML) according to D2487-11 (ASTM, 2011).

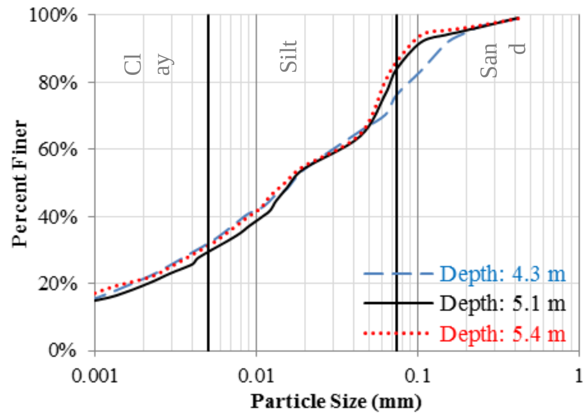

Figure 1. Grain size analysis of samples from different depth levels

2.2 Specimen Preparation

DSS device at UBC is a modified NGI-type (Norwegian Geotechnical Institute type) device (Bjerrum & Landva, 1966) that accommodates a specimen with a diameter of about 70 mm and a height of about 20 mm placed in a wire-reinforced rubber membrane. The relatively undisturbed silt specimens for testing were produced by pushing a sharpened-edge polished stainless steel ring vertically downwards on to the soil samples extruded from thin-walled steel tube samplers that had a slightly larger diameter of ~73 mm,. Using a wire saw, the top and the bottom sides of the specimens were trimmed, leading to a specimen with a height of about 20 mm having smooth top and bottom surfaces. The trimmed specimen was carefully placed in the wire-reinforced membrane for testing.

The reconstituted specimens were prepared from a saturated slurry. To prepare the slurry, initially, a representative potion of dried soil was selected; any clumps of soil were broken down using a pestle. Then, de-aired water was added to the soil while mixing until a homogeneous slurry was formed. The slurry was kept under vacuum for 24 hours for de-airing purposes. The sample was stirred, re-mixed, and shaken occasionally while it was under vacuum, in order to minimize the entrapped air bubbles inside the slurry. The slurry was then transferred to a 300-ml beaker and was allowed to consolidate under its own weight for about 24 hours; at this point, the thin-clear water film formed at the top of the slurry was carefully removed by applying suction. Remaining material was stirred once again, thus preparing a slurry mix that is ready to be gently placed in the specimen cavity surrounded by the wire-reinforced membrane. Efforts were made during specimen placement to minimize the formation of entrapped air in the reconstituted specimen. Reconstituted specimen prepared and placed in the DSS device according to the method described herein would not allow controlling the as placed density.

2.3 Constant-volume Direct Simple Shear Tests

The results presented herein are derived from constant-volume DSS tests. In the DSS device at UBC, test specimens are placed in a wire-reinforced rubber membrane that laterally confines and enforces an essentially constant cross-sectional area and prevents the specimen from localized lateral straining during consolidation and shear deformation. Therefore, by restraining the top and bottom loading platens of the specimen against vertical movement to impose a height constraint, a constant-volume condition can be enforced. 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 (Dyvik et al.1987). Therefore, in this test series, change of vertical stress during constant-volume shearing is interpreted as the equivalent excess pore-water pressure due to shear loading.

The test specimens were initially consolidated to the desired vertical effective consolidation stress (σ'_{vc}), and then subjected to constant-volume shear loading. The application of monotonic shear load was controlled by a constant strain rate of about 10% per hour. Using a double-acting piston that is coupled with an electro-pneumatic pressure regulator (EPR), the cyclic loading was applied in symmetrical sinusoidal cycles of loadings to impose the desired constant cyclic stress ratio [CSR = τ_{cyc} /σ'_{vc}) amplitude on the specimen at a frequency of 0.1 Hz. As an "index" for assessing and comparing the cyclic shear strength, the attainment of 3.75% single-amplitude horizontal shear strain (γ) in a DSS specimen was considered as a criterion for unacceptable performance.

2.4 Test Program

A series of DSS tests were performed on both relatively undisturbed specimens (US) and reconstituted specimens (RS) as shown in Table 2. Monotonic shear tests were performed on specimens prepared from relatively undisturbed samples, consolidated to three consolidation stresses as σ'_{vc}= 100 kPa, 200 kPa, and 400 kPa (i.e., named with Test Nos. US 100M, US 200M, and US 400M respectively). Reconstituted specimens prepared from essentially the same silt samples used in the above three tests were employed for conducting the monotonic shear Tests No. RS 100M, RS 200M and RS 400M at the same three stress levels. The intent here was to study the effect of fabric/microstructure by minimizing the possible effects arising due to variation of other parameters in the specimens. Same approach was used to prepare the counterpart reconstituted specimens for the cyclic tests. All cyclic DSS tests were performed at 200 kPa of consolidation stress with appropriate CSR.

Once a given specimen has been placed in the DSS device and a seating pressure of about 10 kPa was applied, the initial height of the specimen was recorded to define the initial conditions with initial void ratio (e_i). It should be noted that reconstituted specimen prepared from slurry deposition method would not allow controlling the e_i, and from Table 2, it can be seen that e_i of reconstituted specimens were comparatively lesser than those of undisturbed specimens. Estimated preconsolidation stresses ($\sigma'_{pc\text{-}1D}$) from 1-dimensional consolidation tests were 35~45 kPa, whereas estimated effective in-situ overburden stresses ($\sigma'_{v\text{-}insitu}$) were in the range of 41~49 kPa. All DSS tests were conducted at consolidation stress levels that were greater than the estimated pre-consolidation stress (σ'_{pc}) to ensure that the shear loading (either monotonic or cyclic) were applied for normally consolidated test specimens. Post-consolidation void ratios (e_c) are also listed in Table 2. Upon the consolidation process, all DSS tests were performed without any initial static shear bias (i.e. simulating level ground conditions)

Table 2. Test parameters and summary of test results

	Test ID	e_i	σ'_{vc} : kPa	e_c	CSR τ_{cyc} /σ'_{vc}	N_{cyc} [Υ=3.75%]
Undisturbed specimens	US 100M	1.28	101.2	1.06		
	US 200M	1.45	199.9	1.06		
	US 400M	1.21	396.0	0.91		
	US 200-38	1.08	199.4	0.89	0.191	5.8
	US 200-34	1.08	201.2	0.88	0.169	12.8
	US 200-30	1.11	203.4	0.91	0.149	37.8
	US 200-28	1.13	199.8	0.89	0.141	56.8
Reconstituted specimens	RS 100M	0.96	98.5	0.72		
	RS 200M	0.95	201.0	0.68		
	RS 400M	0.86	399.3	0.58		
	RS 200-30	0.95	198.8	0.67	0.152	7.3
	RS 200-26	0.99	200.9	0.66	0.130	19.8
	RS 200-20	0.96	199.2	0.68	0.106	86.8

WC = Average water content of the test specimen computed from the available trimmings from undisturbed specimens and sample portions from reconstituted specimen.
e_i = Initial void ratio after the application of the seating pressure of about 10 kPa
σ'_{vc} = Vertical consolidation stress prior to the application of shearing
e_c = Post-consolidation void ratio prior to the application of shearing
CSR [τ_{cyc} /σ'_{vc}] = Cyclic stress ratio, (cyclic shear stress / initial effective vertical stress at the start of cyclic shearing)
$N_{cyc\ [\gamma=3.75\%]}$ = Number of uniform loading cycles to reach single amplitude shear strain of 3.75%

3 MONOTONIC SHEAR LOADING RESPONSE

The shear stress-strain curves obtained from constant-volume monotonic DSS tests conducted on relatively undisturbed and reconstituted specimens normally consolidated to varying vertical effective stress levels are presented in Figure 2. The stress paths of relatively undisturbed and reconstituted specimens from the same tests are presented in Figure 3. In these figures, continuous lines represent the response of relatively undisturbed specimens while dashed lines represent the response of reconstituted specimens.

Post-consolidation void ratios of the specimens for each of the cases that are presented in Table 2 would assist comparing the packing density of the particles in relatively undisturbed and reconstituted specimens prior to constant-volume monotonic shearing.

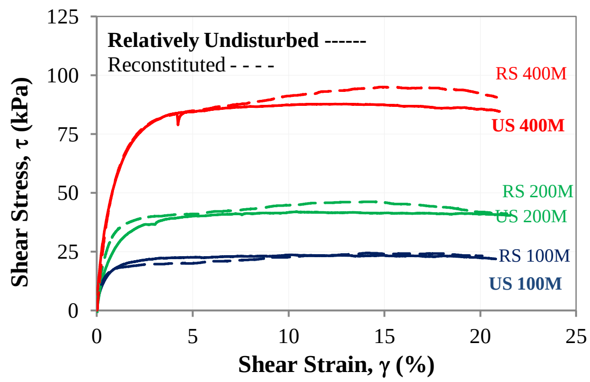

Figure 2. Shear stress-strain response - constant-volume monotonic DSS tests on relatively undisturbed and reconstituted specimens for σ'_{vc} = 100, 200, and 400 kPa.

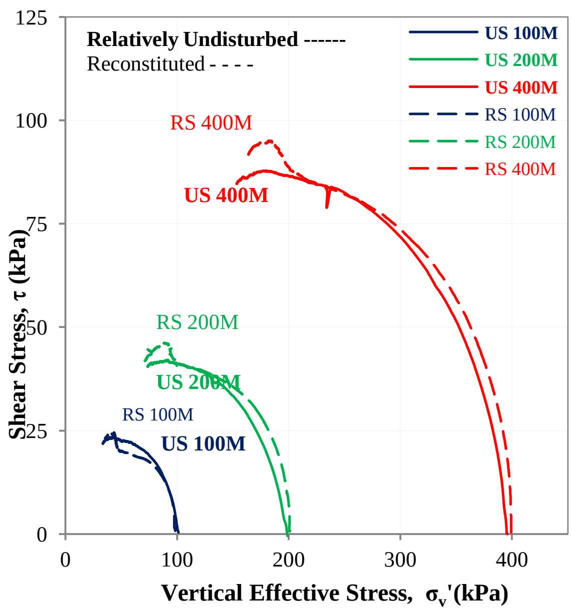

Figure 3. Stress paths - constant-volume monotonic DSS tests on relatively undisturbed and reconstituted specimens for σ'_{vc} = 100, 200, and 400 kPa

From the test results shown in Figure 2 and Figure 3, it can be seen that both undisturbed and reconstituted specimens did not indicate notable stain-softening. Initial stiffness and shear stress-strain characteristics up to about 0.5% shear strain of reconstituted and undisturbed specimens, for a given σ'_{vc}, are almost identical; however, at relatively large shear strain values of about 15%, reconstituted specimens displayed relatively higher shear stress than that of undisturbed specimens. At all tested consolidation stress levels, reconstituted specimens indicate slightly higher peak shear strength than that of undisturbed specimens. It is to be noted that the post consolidation void ratios of the reconstituted specimens are comparatively lesser than that of undisturbed specimens. Typically, comparatively lesser void ratio (denser particle arrangement) results in an increase in shear stiffness and strength, whereas destructuration of natural fabric causes a decrease in shear stiffness and strength. The results presented herein suggest that reconstituted specimens, which had lesser void ratios in comparison to the undisturbed specimens, indicate slightly higher shear resistance against monotonic shear loading. Similar responses have been observed by Fleming & Duncan (1990) for Alaskan silt, when undrained shear strength of undisturbed specimen were compared with that of the specimen. From the results of isotropically consolidated undrained triaxial tests on Alaskan silt, Fleming & Duncan (1990) noted that remolded and reconsolidated specimens showed an increased undrained shear strength of 25% to 40% compared to undisturbed specimens.

On the contrary, experimental studies on silt from Borlánge, Sweden with triaxial testing by Høeg et al. (2000) and on Fraser River silt from Lower Mainland, BC with DSS testing by Sanin & Wijewickreme (2011) reported that reconstituted specimens showed weaker shear resistance and lower undrained shear strength, although the void ratio of reconstituted specimens were lesser (if not similar) than those of undisturbed specimens.

It appears that the net effect arising from the competing tendencies invoked by the void ratio and the fabric/microstructure of test specimen would determine the observed shear response under monotonic loading.

4 CYCLIC SHEAR LOADING RESPONSE

The results obtained from constant-volume cyclic DSS tests (Table 2) that were performed at σ'_{vc} of 200 kPa with appropriate CSRs on undisturbed and reconstituted silt specimens are used herein to compare the cyclic shear performance.

Typical response, observed in terms of the accumulation of shear strain and development of pore water pressure ratio, during the application of cyclic loading in the constant-volume cyclic DSS tests are shown in Figure 4. The results correspond to two tests performed on reconstituted and undisturbed specimens with similar loading condition as σ'_{vc} = 200 kPa and CSR = 0.15 to establish a basis for the comparison. Furthermore, the typical cyclic stress-strain curves and stress-paths obtained from the same DSS tests on undisturbed and reconstituted silt specimens are Figure 5shown in Figure 5. For the clarity of comparison, the cyclic stress-strain and stress path for selected loading cycles (i.e. 1^{st} and 8^{th} loading cycle) are presented in Figure 6.

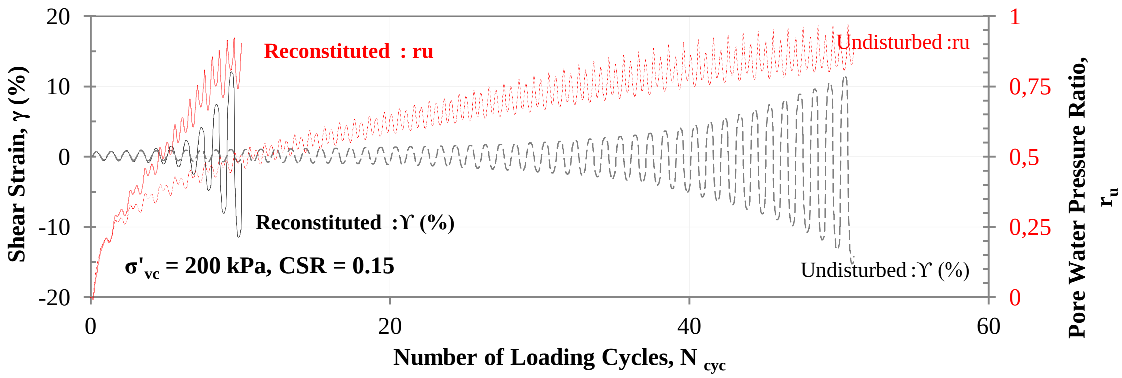

Figure 4. Comparison of the accumulation of shear strain and development of pore water pressure ratio with respect to number of loading cycles in constant -volume CDSS tests of relatively undisturbed and reconstituted specimens

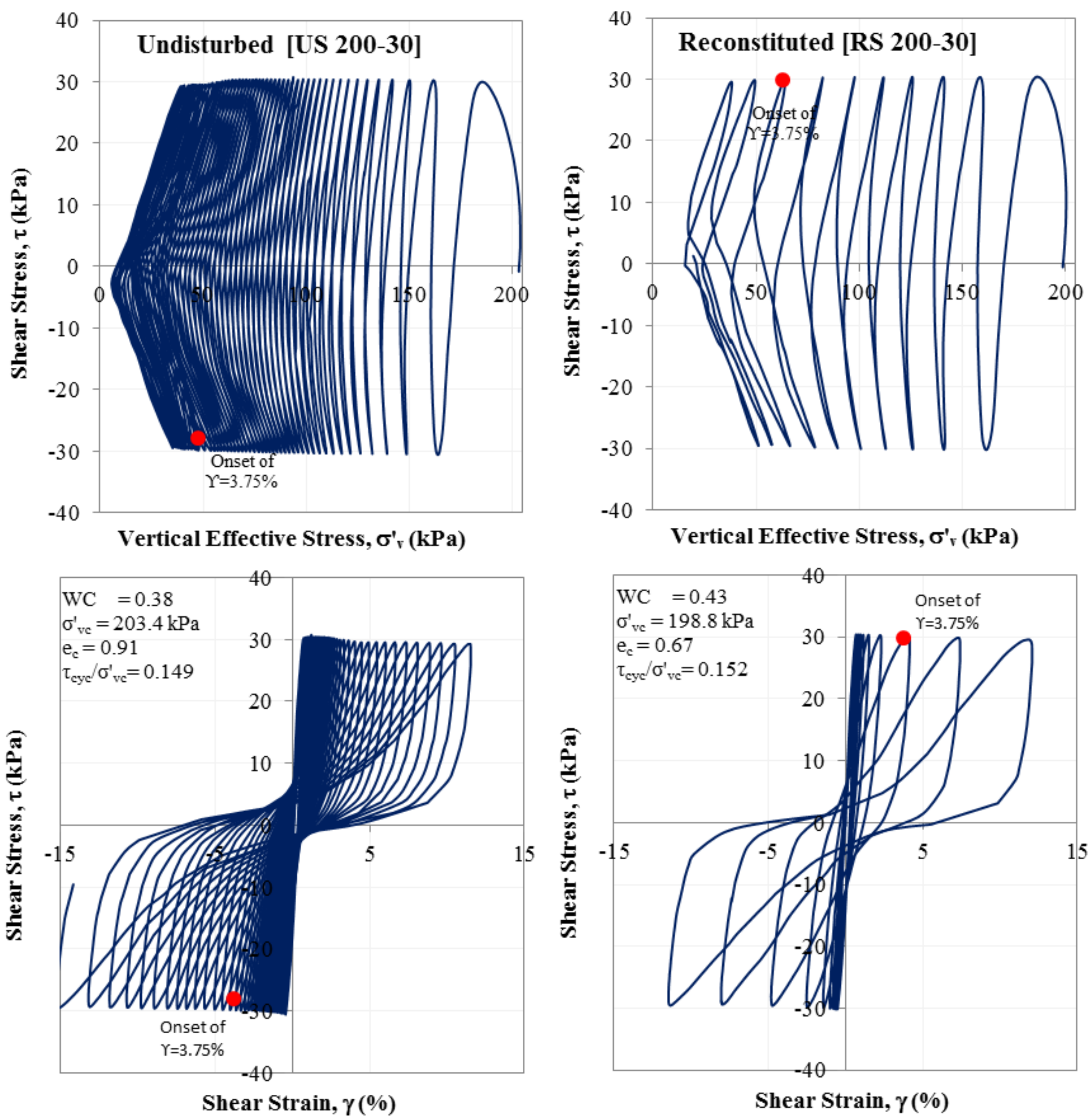

Figure 5. Comparison of stress path and shear stress-strain curves of constant-volume CDSS test on relatively undisturbed (US 200-30) and reconstituted specimen (RS 200-30), at σ'_{vc} = 200 kPa and CSR ~ 0.15

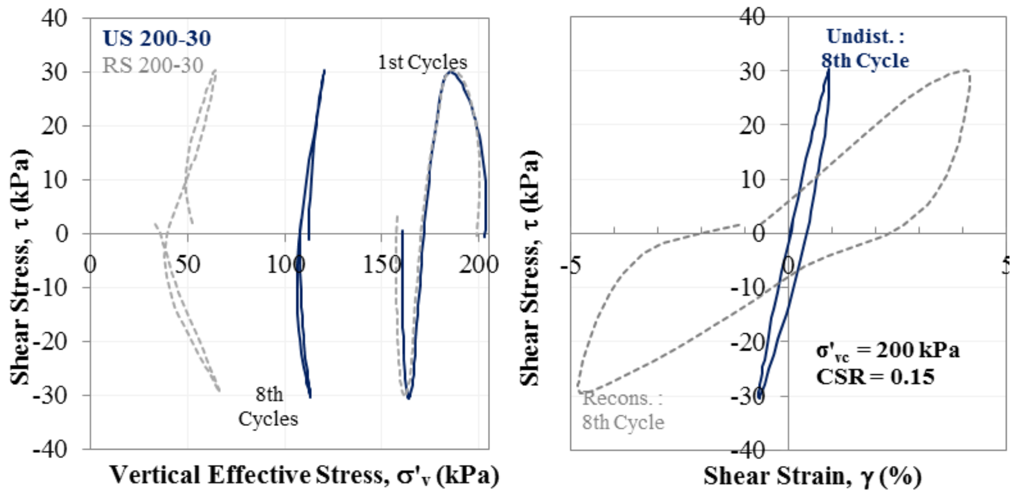

Figure 6. Comparison of stress path and shear stress-strain curves of selected loading cycles during constant-volume CDSS test on relatively undisturbed and reconstituted specimen under similar normally consolidated σ'_{vc} and CSR

Both the reconstituted and undisturbed specimens seem to generally indicate gradual development of pore-water pressure and progressive accumulation of shear strain during cyclic loading. However, as seen from Figure 4 and Figure 5, reconstituted specimen showed a higher rate of pore-water pressure development and shear strain accumulation with respect to number of cycles when compared to those observed in relatively undisturbed specimen.

As may be noted from Figure 5, during the initial loading cycles, both reconstituted and undisturbed specimens display initially contractive behaviour; followed by contractive and dilative responses during loading and unloading portions of cyclic shear stress respectively. Further, both specimens indicated gradual reduction in shear stiffness with increasing number of loading cycles and "cyclic mobility type" strain development. Although not presented herein for brevity, similar behaviour was noted for the other cyclic DSS tests (Table 2) that were performed with different CSRs on reconstituted and undisturbed specimens.

In general, reconstituted specimens indicated higher rate in development of pore-water pressure, accumulation of shear strain and degradation of shear stiffness with respect to number of loading cycles, when compared to those of undisturbed specimens. For example, Figure 6 that compares the shear stress-strain and stress paths for the 8th loading cycle during the Tests No. US 200-30 and RS 200-30 clearly indicated the significant weaker response of reconstituted specimen. The comparison of the stress path for the first loading cycles of US 200-30 and RS 200-30 tests shown in Figure 6 seems to not exhibit any notable difference; however, the differences in strain accumulation, relative degradation of shear stiffness, and reduction of vertical effective stress is significant in 8th loading cycle. This difference in shear response of reconstituted specimens with respect to that of undisturbed specimens can also be shown further by examining the cyclic shear resistance in terms of the variation of cyclic resistance ratio (CRR) versus number of cycles to reach a shear strain of 3.75% as shown in in Figure 7.

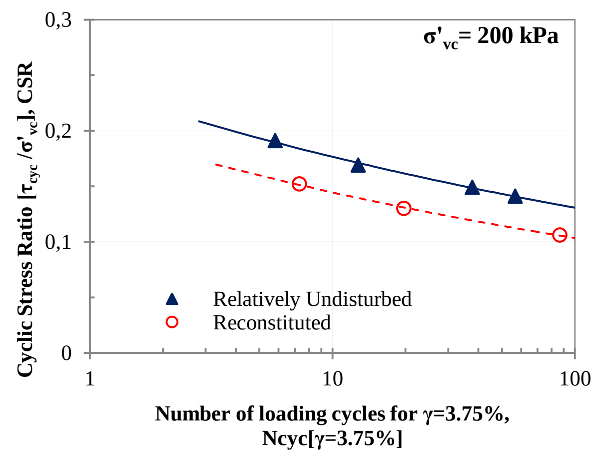

Figure 7. Cyclic stress ratio vs. number of loading cycles for shear strain of 3.75% for reconstituted and undisturbed specimens

The cyclic shear resistance shown in Figure 7 clearly indicates the weaker shear performance of reconstituted specimens in comparison to that of undisturbed specimens under cyclic loading, despite the relatively lesser void ratio of reconstituted specimens. The observed relatively weaker response of reconstituted specimens is in accord with the observations of Wijewickreme & Sanin (2008) and Sanin & Wijewickreme (2011) for reconstituted specimens prepared from Fraser River delta silt. Unlike for the case of monotonic shear loading response presented earlier, it seems that the influence arising from fabric is predominant in the observed cyclic shear resistance, and it has over-shadowed the effect due to the change in void ratio of the reconstituted specimens. It is possible that the evolution of particle structure rearrangement during monotonic loading might be different to that during cyclic loading (which involves cyclic rotation of principal stresses), and these differences might have served as a source for the observed difference behaviour of reconstituted and undisturbed specimens during monotonic and cyclic shear loading.

5 SUMMARY AND CONCLUSIONS

Simple shear loading response of relatively undisturbed silt specimens retrieved from thin-walled samplers and reconstituted specimens prepared from the same material by the slurry deposition was investigated using a series of monotonic and cyclic direct simple shear tests.

When shear strength derived from constant-volume monotonic DSS tests on undisturbed specimens and reconstituted specimens are compared, the reconstituted specimens exhibited slightly higher shear strength than that of relatively undisturbed specimens. Reconstituted specimens, that were prepared from the slurry deposition method showed comparatively lesser void ratio implying denser at a vertical effective stress than that for relatively undisturbed specimens. From the observed monotonic shear response in reconstituted specimens, it appears that the effects on the shear response arising from changes in void ratio have over-shadowed the influence due to the change in fabric and micro-structure.

In contrast to the response observed for the monotonic shear resistance, the observations during cyclic shear tests reveal that the reconstituted specimens consistently exhibit increased rates of pore-water pressure development, strain accumulation, and shear stiffness degradation in comparison to those for relatively undisturbed specimens. In the case of cyclic tests, the effects due to the change of fabric and microstructures in reconstituted specimens seem to be dominant in governing the cyclic shear response than those arising from the void ratio.

These results suggests that the void ratio and confining stress alone are not the only key variables that would control the shear response of fine-grained soils; competing effects from factors such as void ratio and fabric should be carefully considered in predicting the monotonic and cyclic shear loading response of fine-grained materials.

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