Some initial experimental findings on the influence of mode of shear on the monotonic shear response of reconstituted silts

D. Barnes, P. Verma, and D. Wijewickreme
Department of Civil Engineering – University of British Columbia, Vancouver, BC, Canada

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ABSTRACT
An experimental research program has been undertaken to investigate the influence of mode of shear on the monotonic shear response of relatively low plastic reconstituted silt obtained from a soil deposit located in Kamloops, British Columbia, Canada. The consolidated monotonic shear response of the reconstituted silt under undrained triaxial compression, undrained triaxial extension, and constant volume direct simple shear loading conditions were compared. In the triaxial tests, the silt specimens were reconstituted from an initial slurry state and then consolidated to three target effective confining stress levels. At all confining stress levels, the undrained shear strength observed under triaxial compression was observed to be approximately 20% greater than that noted from triaxial extension tests. The undrained shear strength measured from the direct simple shear loading at an effective confining stress level of 100kPa was observed to be similar to that measured in the triaxial extension test. This limited test data suggests similar trends to what has been observed for K_o - consolidated low plastic soft clays.

RÉSUMÉ
Un programme de recherche expérimental a été entrepris pour évaluer l'influence du mode de cisaillement sur la réponse en cisaillement statique du silt reconstitué à plasticité relativement faible, obtenu à partir d'un dépôt de sol à Kamloops, en Colombie Britannique, au Canada. Les réponses de cisaillement statique du silt reconstitué sous compression triaxiale non-drainée, extension triaxiale, et sous charge de cisaillement simple directe à volume constant, ont été comparées. Pour les tests triaxiaux, les échantillons de silt ont été reconstitués à partir d'un état initial boueux, puis consolidés vers trois niveaux de contraintes effectives de confinement ciblées. Pour tous les niveaux de contraintes de confinement, la force de cisaillement sous compression triaxiale a été maintenue à approximativement 20% de plus que celle des tests d'extension triaxiale. La force de cisaillement non-drainée mesurée à partir de la charge de cisaillement simple directe à un niveau de contrainte effective de confinement de 100 kPa correspond à celle mesurée sous tests triaxiaux. Ces données de tests limités suggèrent des tendances similaires à ce qui a été observé pour le K_o d'une argile souple consolidé à faible plasticité.

1 INTRODUCTION

Liquefaction of saturated soils is one of the primary concerns related to the performance of structures located in areas of moderate to high seismicity. Over the past 40 years, the research focus has been mainly on the earthquake response of sands and "relatively clean" sandy soils. The behaviour of silty sands and silts, on the other hand, has been investigated only on a very limited scale. Silt deposits are prevalent in most earthquake-prone soft-soil areas, and there is evidence that areas underlain by such soils have experienced ground deformations and failures, including damage to structures, during past earthquakes (Boulanger et al., 1998, Sancio et al., 2002).

Understanding the undrained monotonic shear response of silts is important in liquefaction assessment, and this knowledge allows the assessment of potential for flow slides and earthquake-induced displacements. The undrained behaviour of natural soils are stress-path dependent. The term stress-path represents variations in both the magnitude of the principal stresses and their directions in relation to a three-dimensional frame of reference, typically expressed with one of the axes oriented in the vertical direction to coincide with the general direction of soil deposition in most natural and man-made soil deposits.

The stress-path dependency of silts is not very well known. This paper presents an experimental study; comparing the undrained monotonic shear response of reconstituted silt under triaxial compression (TC), triaxial extension (TE) at varying effective confining stress levels. The shear response under triaxial loading was then compared with that obtained from direct simple shear (DSS) loading.

2 SHEAR RESONSE OF NATURAL SILTS

The mechanical response of soils is controlled by many factors such as mineralogy, grain size/shape, plasticity, particle arrangement (fabric), microstructure, packing density, initial stress conditions, age, etc. The natural deposition process usually creates an inherent anisotropy in soils both in terms of stiffness and strength. With respect to static loading, research has clearly shown the important effects of soil anisotropy on selection of design strengths for stability problems for low plastic soft clays (DeGroot, 2001) and reconstituted sands (Vaid et al., 1996).

The triaxial device and DSS device are widely used in industry practice for measuring the undrained strength of soils. The DSS device has the ability to test soils with continuous rotation of principal stresses about the vertical axis during shear. However, it is difficult to estimate the stress state in a DSS specimen since the magnitude of the horizontal normal stress is unknown. The triaxial device, on the other hand, allows full control of major and minor principal stresses during cyclic loading. However, in this device, the stress state is limited to scenarios where the major and minor principal stresses are fixed in the vertical and horizontal direction, and only “jump” principal stress rotations from vertical to horizontal and vice versa are feasible.

Natural silts are typically deposited under highly varied geologic conditions making their systematic quantification of stress-strain-strength behavior complex. To add to this complexity, there are only limited studies available to understand the extent and effect of anisotropy that are likely to exist in natural silt deposits. This paper provides some initial observations comparing the mechanical response of reconstituted relatively low plastic silt consolidated to varying target stress levels and sheared under triaxial and DSS loading conditions. The work was conducted at the geotechnical research laboratory at University of British Columbia (UBC). A slurry deposition technique was used to simulate the deposition of natural silts typically found in a fluvial environment.

3 MATERIALS TESTED

The silt material used in this research (named hereinafter as Kamloops silt) originates from the Kamloops silt bluffs on the south side of the South Thomson River which is located just east of Kamloops, British Columbia, Canada. The silt was deposited in a glacial lake referred to as Lake Thomson (Mathews, 1944) during the last deglaciation. Much of the silt was derived from the erosion of the till on the uplands and entered the Thomson Valley in the vicinity of Kamloops. The coarse portion of the till was left on the uplands while the silt was carried into the valley.

The particle size distributions obtained from four specimens of a bulk sample collected from the Kamloops silt bluffs are shown in Figure 1. The average parameters derived from index testing for the silt are summarized in Table 1.

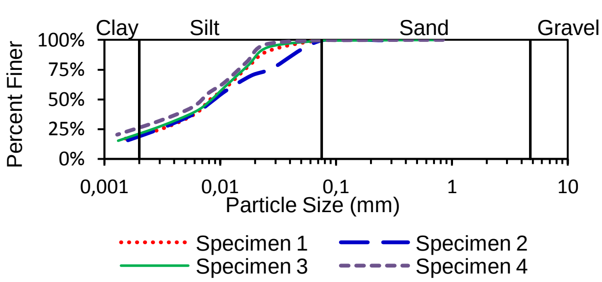


Figure 1. Grain size distribution of Kamloops silt

Table 1. Some properties of reconstituted Kamloops silt

Soil property	Values
Liquid limit, LL (%)	34
Plastic limit, PL (%)	25
Plasticity index, PI	9
Unified soil classification	CL
Specific gravity, G_s	2.76

4 LABORATORY TESTING

A series of experiments comprising consolidated undrained (CU) triaxial and constant volume DSS tests were undertaken to investigate the monotonic shear response of the Kamloops silt. The test program is summarized in Table 2.

Table 2. Summary of the testing program

Mode of Shear	Initial Consolidation Stress Level (σ'_{vc} or σ'_c, Nominal value given)
TC	100
	200
	300
TE	100
	200
	300
Monotonic DSS	100

4.1 Triaxial Testing

A custom built triaxial device at UBC was used for the triaxial shear testing. The UBC triaxial device allows the testing of reconstituted silt specimens having a diameter of approximately 72 mm and height of about 150 mm. A continuous record of test data was obtained by a computer interfaced data acquisition system. The monitored test variables consisted of full-time histories of deviator stress (σ_d), cell pressure (σ_c), pore water pressure (u), axial strain (ε_a) and volumetric strain (ε_v).

During specimen preparation, the reconstituted silt specimens were consolidated on a triaxial base pedestal inside a vacuum split mold with expanded rubber membrane in place (Figure 2). The selected reconstitution method is based on a previous design (Wang et al., 2011), allowing saturation, consolidation and shearing to be completed with the specimen in the same position, minimising any opportunity for specimen disturbance. This is considered to the best technique for simulating the deposition of natural fluvial silt deposits. This paper presents the details of the test program and its main findings.

After several trials, the following procedure was developed to prepare a reconstituted silt specimen for triaxial testing:

1. A silt slurry was prepared by mixing oven dried pulverised Kamloops silt with de-aired water, resulting in a water content of 60%.
2. The silt slurry was then placed in a vacuum desiccator and allowed to soak for three hours while mixing at regular time intervals.
3. The silt slurry was poured into a split vacuum mold through a flexible plastic hose. An extension collar was placed on top of the split mold to allow for the larger volume of slurry required for consolidation (Figure 2).
4. The slurry was left consolidate under self weight for 3 hours.
5. With the objective of obtaining a reasonably consolidated soil specimen, it was required to consolidate the slurry in the mold by application of an external total vertical stress (σ_v) using a separate loading ram (see loading ram on the left side of Figure 2).
6. Firstly, the loading ram was placed on the silt slurry, and the slurry was allowed to consolidate under the weight of the loading ram overnight (i.e., with a loading ram surcharge of approximately 1.8kPa). In preparation for applying load increments as per below, at this point, the loading ram was removed from the extension collar, cleaned and repositioned to minimise friction between the loading ram and extension collar.
7. Then, the next step was to apply vertical stress in an incremental manner on the slurry and allow the slurry to consolidate under each load increment. The loading increments were applied to the specimen using a double acting piston on the UBC triaxial apparatus.
8. Under each load increment, the consolidation progress was monitored by obtaining real-time histories of σ_v and ε_a. The size of load increments was determined based on several trials in order to avoid squeezing of the slurry out of the mold during each load increment.
9. Primary consolidation was achieved under each load increment before increasing to the next load with drainage provided at the top cap and base pedestal.
10. The slurry specimen inside the mold was consolidated to a maximum effective vertical stress (σ'_v) of about 40 kPa. This stress level was found to provide reasonably firm specimen to move forward with completing the specimen preparation work while keeping the initial specimen consolidation stress level at a value less than the minimum isotropic consolidation stress of 100 kPa, contemplated for triaxial testing.
11. At the completion of slurry consolidation (to about ~40 kPa), the loading ram and extension collar were carefully removed and the excess silt above the split mold was carefully trimmed using a wire-saw, resulting in a specimen that was flush with the top of the split mold.
12. The loading ram used for triaxial testing was then carefully placed onto the trimmed specimen. The rubber membrane was flipped up from the vacuum split mold to encapsulate the top cap. An o-ring was used to seal the rubber membrane to the top cap, as usually undertaken in securing specimens for triaxial testing.
13. A 30 kPa vacuum was applied to the specimen via the bottom drainage. The specimen was left to stabilize under vacuum for 30 minutes.
14. At this point, the vacuum split mold was removed for final assembly of the triaxial cell, followed by the application of cell pressure for saturation checks using Skempton B-value testing.

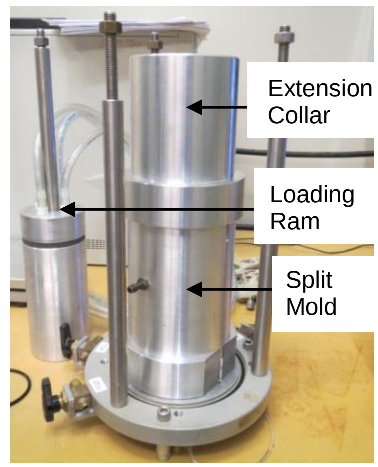


Figure 2. Slurry consolidation device

During triaxial testing, silt specimens were initially consolidated to three predefined hydrostatic effective confining stress (σ'_c); larger than the final slurry vertical consolidation stress of 40 kPa used during specimen preparation. Following consolidation, a variable speed motor was used to conduct consolidated-undrained (CU) testing in either TE or TC modes.

The rate of loading during undrained shearing should be sufficiently slow to allow for pore pressure equilibration within the specimen (Germaine and Ladd, 1988). An appropriate rate of axial strain was selected using the initial slope of volume change versus square root of time curve, obtained during the consolidation phase of the triaxial test. Bishop and Henkel, (1962) suggest using this curve to obtain the time for 100% primary consolidation (t_{100}) and estimate the time to failure during undrained shearing (t_s). Using this method, a rate of axial strain of 6% per hour was found to be sufficiently slow to ensure equilibration of pore water pressure within the specimen.

The triaxial tests were conducted until the specimens experienced a maximum ε_a level in the order of 8-10%.

4.2 DSS Testing

The NGI-type (Bjerrum et al, 1966) DSS device at UBC was used as the test apparatus for monotonic DSS shear testing. The UBC-DSS device allows the testing of a soil specimen having a diameter of approximately 70 mm and height of 20-25 mm. In the DSS device, the specimen diameter is constrained against lateral strain using a steel-wire reinforced rubber membrane. If 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 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 (Dyvik et al., 1987).

A computer interfaced data acquisition system was used to obtain full time-histories of horizontal shear stress (τ), decrease in vertical stress (or equivalent rise in excess pore water pressure, Δu) and horizontal shear strain (γ).

During DSS testing, a single silt specimen was consolidated to a nominal predefined vertical effective stress (σ'_{vc}) of 100kPa, followed by monotonic shearing. The predefined value of σ'_{vc} was selected to allow comparison with TC and TE shearing modes at an equivalent σ'_c. The DSS test was conducted until the specimen reached a maximum γ level of 15%.

5 EXPERIMENTAL RESULTS

5.1 Triaxial Testing

5.1.1 Specimen Consolidation

The void ratio of the specimen in slurry form at the time of pouring (e_o), end of slurry consolidation (e_{sc}) and end of triaxial isotropic consolidation (e_{tc}) are summarised in Table 3. The results indicate similar void ratios at the end of slurry consolidation and a reduction in void ratio with increase in confining stress during triaxial consolidation, thus indirectly indicating the repeatability of the specimen preparation process.

Table 3. Summary of specimen void ratio

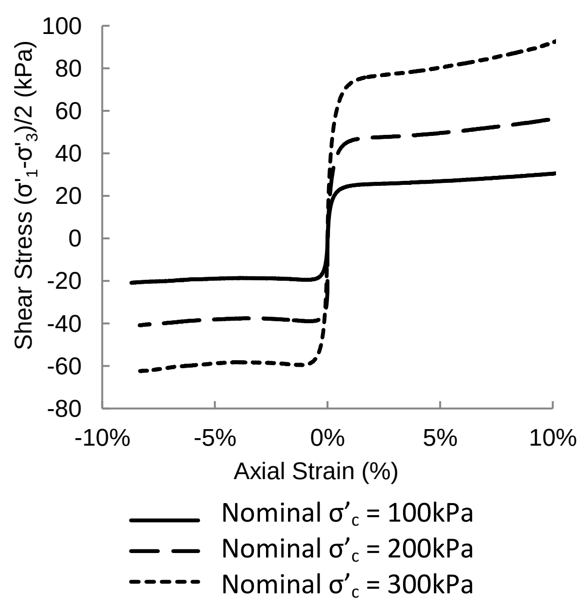
Mode of Shear	Nominal σ'_c	e_o	e_{sc}	e_{tc}
TE	100	1.651	0.964	0.864
	200	1.645	0.946	0.802
	300	1.645	0.914	0.760
TC	100	1.643	0.951	0.856
	200	1.645	0.943	0.793
	300	1.647	0.969	0.759

5.1.2 Stress-strain and stress path results

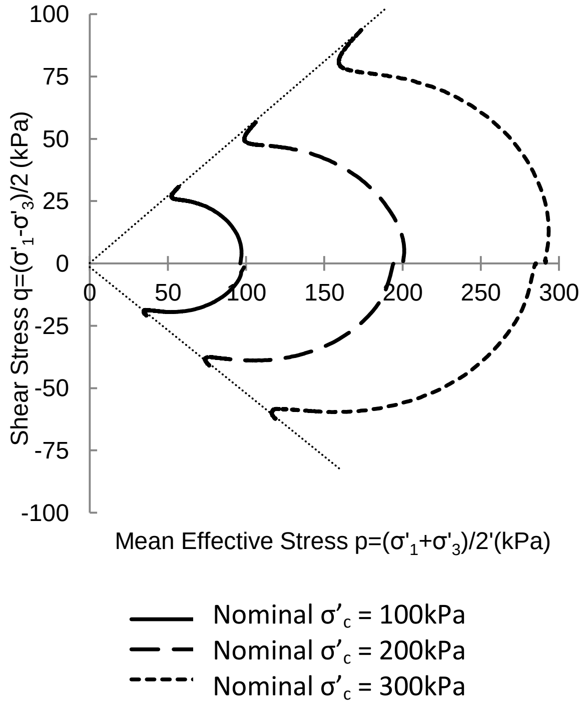
The typical stress-strain and stress path response from CU triaxial tests performed under TC or TE modes of shearing on reconstituted specimens of Kamloops silt initially consolidated to σ'_c of 100, 200, and 300 kPa are presented in Figure 3.

As may be noted, all specimens displayed an initial contractive response followed by a dilative response when the specimens reached a phase transformation stress state. Moreover, the specimens exhibited a mostly strain hardening response with the effect amplified with increase in confining stress.

Figure 4 shows stress paths normalized with respect to σ'_c. The normalized stress paths for all σ'_c fall within a relatively narrow range. In general, the “normalizable” response of normally consolidated silt is similar to that typically observed for normally consolidated clays (Atkinson et al., 1978). The mobilized angles of friction at maximum obliquity (ϕ_{mob}), mobilized angle of friction at phase transformation (ϕ_{pt}), and mobilized undrained shear strength (s_{mob}) at relatively large strain are summarized in Table 4. As may be noted, a reasonably common value of ϕ_{max} and ϕ_{pt} can be observed for all tests.

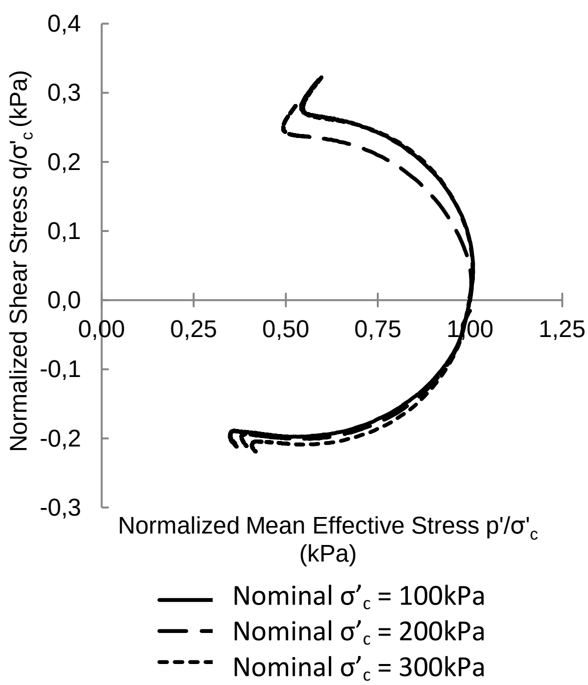


(a)



(b)

Figure 3. CU triaxial static shear response of Kamloops silt: (a) stress-strain and (b) stress path response



(c)

Figure 4. CU triaxial static shear normalized stress paths

Table 4. Summary of Soil Parameters

Mode of Shear	Nominal σ'_{vc}/σ'_c	ϕ_{mob} (deg)	ϕ_{pt} (deg)	s_{mob} (kPa)
Monotonic DSS	100	-	-	19
TC	100	33	32	31
	200	33	32	58
	300	33	32	94
TE	100	35	34	21
	200	32	31	41
	300	32	30	62

5.2 Comparison with DSS testing

Figure 5 shows a comparison of the CU stress-strain behaviour of Kamloops silt under TC, TE modes of shearing with that derived from DSS. The results obtained at a nominal effective confining stress level of 100 kPa are compared. The void ratio at end of consolidation for the DSS test (e_{vc}) and triaxial tests (e_{tc}) are provided on the figure and indicate that e_{vc} values are in reasonable agreement with e_{tc} when consolidated to an equivalent σ'_{vc}.

At larger strains the DSS measures a slight strain softening response. This is in contrast to the TC and TE tests results which exhibit dilation (or phase transformation) at larger strains. Furthermore, the shear strength measured in DSS was similar to that measured in TE and the shear strength measured in TE/DSS was approximately 80% lower than the shear strength measured in TC.

Previous research on K_o-consolidated low plastic soft clay has demonstrated that the undrained shear strength under TC can be as high as twice of that under TE and the undrained shear strength measured from DSS tests generally fall closer to the TE mode of shearing (DeGroot, 2001). The limited test data presented in this paper suggests that this trend is also observed in reconstituted silts.

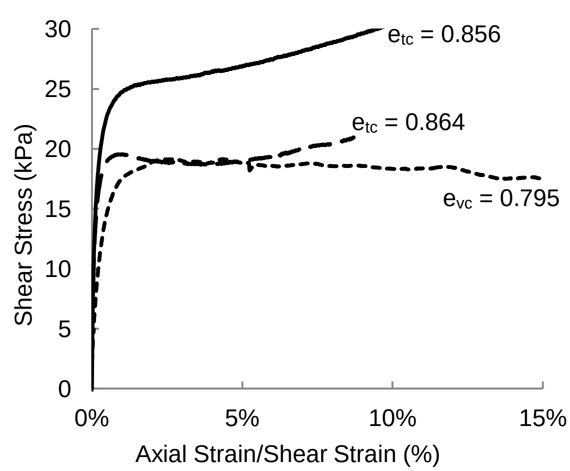


Figure 5. Comparison of DSS, TC and TE behaviour at σ'_c , $\sigma'_{vc} \cong$ 100kPa

6 SUMMARY AND CONCLUSIONS

The static shear response of reconstituted relatively low plastic Kamloops silt, originating from the interior of the Province of British Columbia, Canada was investigated using the triaxial and DSS devices. The silt specimens were prepared using a slurry deposition method considered most representative for simulating deposition of natural silts found in fluvial environments.

CU triaxial test results indicated that the Kamloops silt specimens, initially consolidated to three target effective confining stress (σ'_c) levels, developed an initially contractive response followed by dilation at phase transformation. The mobilized friction angle at phase transformation and mobilized friction angle at maximum obliquity was found to be similar in TC and TE and essentially independent of the applied effective confining stress. The stress paths normalized with respect to σ'_c. fall within a relatively narrow range. This "normalizable" response is similar to that typically observed for normally consolidated clays.

Constant volume DSS tests, initially consolidated to an equivalent target vertical equivalent effective stress level (σ'_{vc}) of 100kPa developed a contractive, slight strain softening type response with no clear indication of phase transformation. The shear strength measured in DSS was found to be similar to the shear strength measured in TE at an equivalent confining stress. This limited test data is in general agreement with the results of low plastic soft clays (DeGroot, 2001).

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