MONOTONIC SHEAR LOADING RESPONSE OF RECONSTITUTED NATURAL SILT WITH INITIAL STATIC SHEAR STRESS

P. Verma¹ and D. Wijewickreme²

ABSTRACT

The monotonic shear loading response of reconstituted natural silt with initial static shear bias (α) was investigated using constant-volume direct simple shear (DSS) tests. Natural silt for the present experimental investigation originates from Kamloops benchland deposits, located on the south side of South Thompson River in Kamloops, British Columbia, Canada. Silt specimens initially consolidated to varying vertical effective confining stresses (σ’vc) and initial static shear stresses (τstatic) were subjected to constant-volume monotonic shear loading in different directions with respect to the applied static shear stress. Under similar α values, the shear resistance was found to increase with increasing σ’vc levels and when normalized, the effective stress paths appeared to generally coincide indicating stress history normalizability. Under similar σ’vc values, the shear resistance was observed to increase with increasing α values for specimens where the monotonic shear loading was applied in the same direction as the applied initial static shear stress. This trend was not observed when the test specimens were sheared in an opposite direction to the applied initial static shear stress under similar σ’vc and varying α values. All silt specimens displayed a prominent contractive tendency in spite of variation in the confining stress levels, initial static shear bias levels, and shearing directions, and the behavioral patterns observed for the tested silt material under monotonic DSS loading was found similar to those typically observed for clays.

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Introduction

Liquefaction susceptibility of saturated fine-grained silty soils is often a geotechnical concern. Evidence from recent earthquakes has suggested that the seismic behavior of certain saturated low plastic fine-grained soils are complex, and could undergo earthquake-induced softening and strength reduction [1–3]. A good understanding of the undrained monotonic shear response of these soils is an important consideration in liquefaction assessment as it provides insights into the fundamental soil behavior. Such an understanding can also effectively aid in interpreting the beha-

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-vioural patterns as observed in the cyclic shear tests.

The geotechnical problems in real-life involve both level as well as sloping ground configurations. Under static conditions, an element of soil beneath a level ground does not have an initial static shear stress on its horizontal plane. A term “no static shear stress bias” is commonly referred to describe this stress state. In contrast, a sloping ground induces finite static shear stresses on the horizontal plane within a soil mass. The term “static shear stress bias” is generally used to represent the stress state of an element of soil beneath such sloping ground [4–7]. The relative magnitude of static shear stress ($\tau_{\text{static}}$) on a horizontal plane is generally assessed by normalizing it with respect to the initial vertical effective confining stress ($\sigma'_{vc}$). The resulting parameter $\tau_{\text{static}}/\sigma'_{vc}$, represented as $\alpha$, for a level ground configuration, is equal to zero [8].

To simulate the sloping ground conditions during laboratory element testing, soil specimens are consolidated with an applied initial static shear stress $\tau_{\text{static}}$; the monotonic shear loading is typically imposed in the same direction as the applied initial static shear stress. However, in the field, the directions of these stresses may not necessarily be in harmony (e.g., ice loading scenario in an offshore structure). Considering this background, the effects of initial vertical confining stress, static shear stress bias, and shearing direction on the monotonic shear loading response of fine-grained reconstituted silt with varying $\alpha$ values are studied as a part of a comprehensive experimental research program on the mechanical response of silts at the University of British Columbia (UBC), Vancouver, Canada.

This paper presents the factual findings from the tests conducted using the constant-volume direct simple shear (DSS) device as it is considered to effectively mimic the rotation of principal stresses as encountered under field loading conditions [9]. In this experimental study, reconstituted test specimens were preferred over relatively “undisturbed” specimens as the former would lead to more controlled, homogenous, and uniform test specimens (with repeatability) without being impacted by the natural variability - that is common with respect to undisturbed soils.

**Material Tested**

The silt material for the present study originates from Kamloops benchland deposits, located on the south side of the South Thompson River just east of Kamloops, in the province of British Columbia (BC), Canada. The fine-grained deposits in the area originated from upland glacial tills that was subjected to erosion during the last deglaciation. The eroded fine-grained material entered the Thompson Valley in the vicinity of Kamloops and got deposited uniformly in a glacial lake referred to as Lake Thompson [10]. The coarse portion of the till was left on the upland while the fine-grained deposits were carried into the valley. Gradually, the water from the glacial lake drained out to re-establish the South Thompson River which carved the dry old lake deposits to form the benchlands of silts [11].

Bulk (disturbed) soil samples for testing were obtained from the top of one of the bluff exposures of these benchland deposits. The chosen site for sampling had moderate to steep slopes with an approximate elevation of 225 meters above sea level. The collected silt material during visual inspection was found to be in dry condition and pale greyish in color. Upon retrieval, the relatively intact blocks of silt were found to break down easily into smaller thick pieces along a horizontal bedding plane suggesting that the silt was likely deposited horizontally under gravity. Visually, no sand layers were observable in-between horizontal bedding planes.
Particle size distribution curves obtained from hydrometer and sieve analysis on four randomly selected silt samples are presented in Fig. 1. As seen from figure 1, the soil comprises of ~15% to ~20% clay respectively with predominant silt-size particles. These results further confirmed the uniformity of the silt deposits as previously noted from the available geological information. The specific gravity of the tested silt material was determined as 2.76; the average plasticity index was determined as 9, and the tested soil was classified as low-plastic silt (ML) in accordance with the ASTM standards [12]. Average soil parameters derived from index testing are summarized in Table 1. The derived index properties are in close agreement with Evans and Buchanan [13].

The choice of this silt as the test material for the current study was considered reasonable because of its geographic uniformity in deposition, natural abundance, and ease of access for sampling. These are some of the important considerations when the intent is to perform a significant number of soil element tests on uniform and homogenous specimens along with repeatability.

![Figure 1. Particle size distribution of randomly selected samples of Kamloops silt.](image)

**Table 1. Index parameters of the tested soil.**

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>Average Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit, LL (%)</td>
<td>33 ~ 34</td>
</tr>
<tr>
<td>Plastic limit, PL (%)</td>
<td>23 ~ 26</td>
</tr>
<tr>
<td>Plasticity Index, PI</td>
<td>~ 9</td>
</tr>
<tr>
<td>Unified Soil Classification</td>
<td>ML</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.76</td>
</tr>
</tbody>
</table>

**Test Apparatus**

The direct simple shear (DSS) device at UBC was used as a test apparatus for the present investigation. The UBC-DSS device is a modified Norwegian Geotechnical Institute (NGI) type test device [14]. In the test device, a cylindrical soil specimen (~70 mm diameter and ~20-25 mm height) is placed inside a steel-wire reinforced rubber membrane which ensures a state of zero lateral strain during consolidation and shear loading. If required, a constant-volume condition
could be enforced by clamping the top and the bottom platens of the specimen against vertical movement. This provides a height constraint in addition to the lateral restraint from the steel-wire reinforced rubber membrane. This is an alternative to the commonly used approach of maintaining the constant-volume condition by suspending the drainage of a saturated specimen. Past researchers [9,15] have shown that the decrease (or increase) in the vertical stress in a constant-volume DSS test is essentially equal to the increase (or decrease) of excess pore water pressure (Δu) in an undrained DSS test where the near constant-volume condition is maintained by not allowing the mass of pore water to change. Detailed description about the UBC-DSS device is available in Soysa [16].

Specimen Preparation

In this study, the DSS tests were conducted on reconstituted soil specimens which were formed from a saturated slurry. Firstly, a known weight of dry pulverized silt sample was added to a known quantity of de-aired water in a glass beaker and then thoroughly stirred to achieve a homogenous "paste". The soil slurry was then kept under vacuum for an approximate period of 24 hours. This allowed the soil particles to settle under its own weight. The soil slurry was intermittently stirred, re-mixed, and shaken to minimize any entrapped air bubble inside the mixture. After the end of ~24 hour period, the soil slurry was carefully stirred once again and removed from the vacuum application. The soil slurry was then spooned into the DSS cylindrical cavity (formed by a mold) with the steel wire-reinforced membrane to prepare the soil specimen for testing. This step was executed carefully to avoid any air entrapment within the soil specimen and to achieve an even top surface.

The above-explained reconstitution technique has been also used in many previous research studies at UBC and is considered to better mimic the in-situ natural deposition of the silt in a river environment [16,17] compared to other soil specimen reconstitution techniques such as moist-tamping.

Testing procedures and Test Program

Upon careful spooning of soil slurry into the DSS cavity to achieve an initial specimen height of approximately 25 mm, the top platen of the test device was brought in contact with the top surface of the specimen so that it would be subjected to a relatively small vertical confining stress (i.e., "seating" load less than 10 kPa). The small seating pressure of ~10 kPa ensured that the top and the bottom platens of the test device were firmly in contact with the test specimen.

The specimens placed in the mold was initially allowed to consolidate under its own weight and the applied small seating pressure (of less than 10 kPa). After the initial setup and the self-weight consolidation, the vertical load on the test specimens were increased in an incremental manner to meet the desired target vertical effective confining stress (σ′vc) level as required by the test parameters of the DSS testing. After the end of the consolidation phase, the specimens were subjected to static shear stress (τstatic) to meet the desired initial static shear stress bias (α=τstatic/σ′vc). The desired static shear stress (τstatic) was applied slowly and incrementally under drained conditions until both vertical and shear strains were stable. Upon completion of static shear bias phase, the specimens were subjected to constant-volume monotonic shear loading which was
applied using a strain-controlled loading system with a rate of approximately 10% shear strain per hour. The UBC-DSS device allows the user to select the direction of monotonic shear loading. Thus, the direction of the applied monotonic shear loading can be controlled according to the test requirements.

As a part of this study, seventeen constant-volume monotonic direct simple shear (MDSS) tests were performed on reconstituted natural silt specimens. The MDSS test program for this study (identified by different test series names) is summarized in Table 2. The constant-volume MDSS tests were conducted on test specimens initially consolidated to varying vertical effective confining stress levels ($\sigma'_{vc} \leq 300$ kPa) and static shear bias level ($\alpha \leq 0.20$). For test series A to D, the direction of applied monotonic shear loading was in the same direction as the applied initial static shear stress. On the contrary, for test series E, the direction of the applied monotonic shear loading was applied in the opposite direction as the applied initial static shear stress. The intent of the test program was to study the effect of initial vertical effective confining stress, static shear stress bias, and shearing direction on the monotonic shear loading response of fine-grained reconstituted silt.

<table>
<thead>
<tr>
<th>TEST SERIES</th>
<th>TEST ID</th>
<th>WC (%)</th>
<th>$e_i$</th>
<th>$\sigma'_{vc}$</th>
<th>$e_c$</th>
<th>$\alpha$</th>
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<tr>
<td>A</td>
<td>KS 100-00-M</td>
<td>48.01</td>
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<td>98.8</td>
<td>0.80</td>
<td>0.00</td>
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<td>201.5</td>
<td>0.70</td>
<td>0.00</td>
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<tr>
<td></td>
<td>KS 300-00-M</td>
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<td>1.32</td>
<td>297.0</td>
<td>0.65</td>
<td>0.00</td>
</tr>
<tr>
<td>B</td>
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<td>44.98</td>
<td>1.24</td>
<td>102.8</td>
<td>0.73</td>
<td>0.05</td>
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<td>0.05</td>
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<td>C</td>
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<td>101.2</td>
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<td>301.9</td>
<td>0.63</td>
<td>0.10</td>
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<td>D</td>
<td>KS 100-15-M</td>
<td>47.13</td>
<td>1.30</td>
<td>102.5</td>
<td>0.71</td>
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<td>1.35</td>
<td>101.6</td>
<td>0.71</td>
<td>0.15</td>
</tr>
</tbody>
</table>

WC: Average water content of the test specimen. $e_i$: Initial void ratio. $\alpha$: Initial static shear stress bias. $\sigma'_{vc}$: Vertical effective consolidation stress.

table: Test Program: Test parameters and Summary of Test Results

Test Results and Discussion

Effect of initial vertical effective confining stress

The monotonic shear loading response from the test series A, B, C and D were used to study the effect of initial vertical effective confining stresses on the monotonic response of Kamloops silt. Fig. 2 displays the typical shear stress-strain, effective stress-path, and normalized stress path responses obtained from constant-volume MDSS tests conducted on Kamloops silt specimens consolidated to varying $\sigma'_{vc}$ ranging from 100 kPa, 200 kPa, and 300 kPa and static shear stress
bias levels ranging from 0 to 0.15. As notable from shear stress-strain plots in Fig. 2 (I), the shear resistance tends to increase with increasing shear strain level until a peak value is reached beyond which the magnitude of shear stress remains almost unaffected for all the tests regardless of varying vertical confining stress (~100 kPa to ~300 kPa) and initial static shear bias (0 - 0.15) levels. In other words, the tested specimens displayed a behavior of no "strain-softening". From Fig 2 (I), it is also notable that under similar $\alpha$ values, the shear resistance increases with increasing $\sigma'_{vc}$ levels.

From the effective stress paths in Fig. 2 (II), it can be observed that the tested silt material displayed a prominent contractive behavior irrespective of the level of confining stresses and initial static shear bias. For all the tests, the effective stress path seems to follow a consistent pattern. This is further evident in Fig. 2 (III) where the effective stress paths are normalized with vertical effective confining stresses. The normalized stress paths appear to coincide or fall within a narrow range for all the tests indicating that the behavior of the tested natural Kamloops silt is stress-history-normalizable regardless of the magnitude of vertical effective confining stress levels up to 300 kPa and initial static shear bias up to 0.15. Similar stress-history-normalizability have been previously noted by Sanin & Wijewickreme [18] for relatively undisturbed, normally consolidated, channel-fill Fraser River silt and by Seidalinova [19] for reconstituted gold tailings. Ladd [20] also observed similar stress-history-normalizability of clay from isotropically consolidated undrained triaxial tests.

**Effect of static shear bias and shearing direction**

Fig. 3 displays the normalized shear stress-shear strain and normalized stress path responses of Kamloops silt specimens initially consolidated to similar $\sigma'_{vc}$ of ~ 100 kPa with an initial static shear bias of 0, 0.05, 0.10, 0.15, and 0.20, and then subjected to constant-volume MDSS loading in the same direction as the applied $\tau_{static}$. As notable from normalized shear stress-shear strain plot from Fig. 3, the shear resistance for the silt specimen tested at $\tau_{static}/\sigma'_{vc} = 0.20$ initially increases with increasing shear strain until a peak is reached followed by a decrease in shear resistance with further increase in the strain levels. This behavior is different than the other specimens tested at lower $\alpha$ levels where a response of no "strain-softening" is observed.

The tested silt at $\tau_{static}/\sigma'_{vc} = 0.20$ also deformed in a contractive manner as indicated by the normalized effective stress-path response in Fig. 3 and no phase transformation is observed. Furthermore, from Fig 3[I] it is notable that the mobilized shear resistances for the test specimens increases with increasing $\alpha$ up to 0.20. This trend is however not observed for specimens tested at $\alpha = 0.0$ and $\alpha = 0.05$ except at shear strain level less than 1%. Similar increase in shear strength with increasing $\alpha$ was also observed by Andersen [21] for quick clay, Yasuhara et al. [22] for Keuper marl silty clay, Hyodo et al. [23] for high plasticity marine clay, and Sanin [17] for channel-fill Fraser River silt. Andersen [19] highlighted that neglecting the shear strength increase during the stability analysis of slopes under undrained loading could led to conservative geotechnical designs.

Fig. 4 directly compares the normalized shear stress-shear strain and normalized effective stress path responses of Kamloops silt specimens initially consolidated under similar $\sigma'_{vc}$ of ~ 100 kPa with different initial static shear bias and then subjected to constant-volume MDSS loading in the opposing direction to the applied static shear stress. As notable from Fig. 4, the tested silt
specimens displayed a behavior of no "strain-softening" regardless of the direction of the shearing.

Figure 2.  Constant-volume monotonic DSS test results on reconstituted Kamloops silt consolidated to varying $\sigma'_v$ levels with initial static shear bias of 0, 0.05, 0.10, 0.15: [I] Shear stress-strain; [II] Effective stress path; [III] Normalized effective stress path.
It is also important to note here that the normalized shear stress-shear strain responses of the specimens subjected to constant-volume MDSS loading in the opposite direction to the applied \( \tau_{\text{static}} \) appear to coincide regardless of the magnitude of initial static shear bias. This behavior is, however, different for the test specimens where the shearing direction was applied in the same direction as the initial static shear stress - in which an increase in the mobilized shear resistance was observed with increase in static shear stress. All the test specimens displayed a prominent contractive tendency with no phase transformation regardless of the shearing direction indicating that the response of tested silt is similar to that typically observed for normally consolidated clays.

Figure 3. Constant-volume monotonic DSS test results on reconstituted Kamloops silt consolidated to similar \( \sigma'_{\text{vc}} \) levels of \(~100\) kPa with initial static shear bias of 0, 0.05, 0.10, 0.15, 0.20: [I] Normalized shear stress-strain; [II] Normalized effective stress path.

Figure 4. Comparison of constant-volume monotonic DSS test results on reconstituted Kamloops silt consolidated to similar \( \sigma'_{\text{vc}} \) levels of \(~100\) kPa with initial static shear bias of 0, 0.05, 0.10, 0.15: [I] Normalized shear stress-strain; [II] Normalized effective stress path.
Conclusions

An experimental research program has been undertaken at the University of British Columbia (UBC), Canada to assess the mechanical response of silts. As a part of this research effort, laboratory data generated from a series of constant-volume monotonic direct simple shear (DSS) testing is examined to study the effect of initial vertical confining stress ($\sigma'_{vc}$), static shear stress bias ($\alpha$), and shearing direction on the monotonic shear loading response of fine-grained reconstituted Kamloops silt with varying $\alpha$ values.

Under monotonic shear loading, the tested specimens displayed a prominent contractive tendency regardless of the initial static shear bias up to $\leq 0.20$, confining stress level up to $\leq 300$ kPa, and different shearing directions. Under similar $\alpha$ values, the shear resistances for all the test specimens were found to increase with increasing $\sigma'_{vc}$ levels. A behavior of no "strain softening" was notable for all the specimens tested with varying initial static shear bias level up to $\leq 0.15$ and confining stress up to $\leq 300$ kPa. The tested silt displayed a strain softening behavior with further increase in level of $\alpha$.

The effective stress path responses when normalized with the initial effective confining stresses were found to almost coincident (or fall within a narrow range) irrespective of the level of $\alpha$ and $\sigma'_{vc}$. Under similar $\sigma'_{vc}$ values, the mobilized shear resistances for the test specimens were observed to increase with increasing initial static shear bias up to $\leq 0.20$ when the direction of the monotonic shear loading was applied in the same direction with the applied static shear stress. When the direction of shearing with respect to the direction of the applied static shear stress was reversed no noticeable difference in the mobilized shear resistances were observed with increasing initial static shear bias up to $\leq 0.15$.

The behavioral patterns observed from the present experimental investigation suggests that the response of tested silt was similar to that typically observed for normally consolidated clays.

Acknowledgments

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References


