Response of undisturbed and reconstituted low-plastic fine-grained soils

Réaction monotonique de cisaillement des spécimens non remaniés et reconstitués du silt à faible plasticité

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ABSTRACT

The monotonic shear response of natural low-plastic Fraser River silt was investigated using constant volume direct simple shear tests, employing specimens prepared from undisturbed field samples and by reconstitution of the same silt material at different initial confining stress levels. The specimens of undisturbed silt, despite having a looser density under identical consolidation stress conditions, exhibited extensively more dilative response and larger shear resistance in comparison to those displayed by counterpart reconstituted specimens. In addition to consolidation stress conditions and resulting void ratios, it appears that other naturally inherited parameters such as soil fabric and aging effects would critically influence the shear response of natural silt. It is possible that the shear response observed from reconstituted specimens may result in unduly conservative design parameters, in turn, demonstrating the value testing specimens from undisturbed samples to assess the expected field behaviour of natural silt.

RÉSUMÉ

La réaction monotonique de cisaillement du silt naturel à faible plasticité du delta du fleuve Fraser a été étudiée en utilisant des essais de cisaillement simple direct (DSS) cyclique à volume constant. L'échantillonnage provient de spécimens non remaniés ainsi que de spécimens reconstitués à des niveaux d'efforts de confinement. Même s'ils sont moins denses que dans des conditions identiques de consolidation, les échantillons non remaniés ont démontré une plus grande dilatation et une plus grande résistance de cisaillement comparativement aux spécimens reconstitués. En plus de la consolidation et de l'indice des vides, il semblerait que d'autres facteurs tels que l'assemblage du sol et les effets du vieillissement viendrait influencer le cisaillement du silt naturel. Puisque le cisaillement observé sur les échantillons reconstitués résulterait en paramètres de conception trop sécuritaires, il serait préférable d'utiliser des échantillons non remaniés afin d'évaluer la réaction sur le terrain du silt.

Keywords: monotonic response, natural silt, reconstituted silt, direct simple shear.

1 INTRODUCTION

Fine-grained silty soils with high levels of saturation are commonly found in 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 and Idriss 2006; Bray and Sancio 2006). Although wide-ranging studies have been undertaken to understand the performance of sands, the available published information on the undrained shear response of fine-grained soils with respect to earthquake loading is limited (Polito and Martin 2001; Boulanger et al. 1998; Bray and Sancio 2006; Sanin and Wijewickreme 2006a; Sanin and Wijewickreme 2006b; Wijewickreme et al. 2005). In particular, there is a need for understanding of the response of low plastic silts in a more fundamental manner, and laboratory testing plays an important role in this regard.

The use of good quality "undisturbed" soil specimens is an important consideration in geotechnical laboratory testing to understand the element behaviour of a given field soil mass. Although the ability to obtain reasonable good quality samples of low plastic silt deposits has already been demonstrated (Bray and Sancio 2006; Sanin and Wijewickreme, 2006a), reconstituted specimens are still in use as a way of investigating the laboratory shear response of silts; this is primarily due to the advantages in terms of cost and effort in preparing reconstituted soil specimens in comparison to obtaining undisturbed samples from the field. The influence of specimen reconstitution technique on laboratory observed soil behaviour, and the differences in the fabric and mechanical response between undisturbed and reconstituted samples of sand and silty sands has been widely studied (e.g., Oda 1972; Vaid and Sivathayalan 2000). The effect of specimen reconstitution on the performance of silty soils has also been studied and significant differences in behaviour have been found between undisturbed and reconstituted specimens (e.g., Høeg et al. 2000; Long et al. 2001).

Mainly through extensive research on sands, it has been well established that the response of a given soil to monotonic and cyclic shear loading is controlled by many parameters such as packing density, microstructure, fabric, level and duration of cyclic loading, confining stress, initial static bias, etc. These parameters have been noted to primarily govern the development of volume change and/or excess pore water pressures, stiffness, and strength in a soil mass during shear and, in turn, controlling the overall response. While cyclic shear tests are valuable in assessing the performance of soils under seismic loading conditions, data from monotonic shear tests have often provided insight into the fundamental soil behaviour and assisted interpretation of the behavioural patterns observed in cyclic shear tests (Vaid and Chern 1985).

In consideration of the above background, this paper presents the results from a series of monotonic shear tests conducted on undisturbed and reconstituted specimens of low plastic silt. The tests were undertaken as a part of a major research program that is currently underway at the University of British Columbia, Vancouver, Canada, to study the mechanical response of natural and man-made fine-grained soil deposits.

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2 MATERIAL TESTED AND TEST PROGRAM

The database included in this study comprises results from monotonic constant volume direct simple shear (DSS) tests performed on relatively young, uniform channel-fill silt obtained from the Fraser River Delta of the Province of British Columbia, Canada. The Fraser Delta sediments have a thickness of up to 300 m, and consist of: surficial fills of variable depth, overbank silts extending up to 6 m in thickness overlying up to 15 m in thickness of deltaic sands, which are then underlain by inter-layered sand and fine-grained materials. For the present study, undisturbed samples of the upper natural silt were obtained using fixed piston tube sampling with a specially fabricated stainless steel, thin-walled tube with no inside clearance (~75 mm diameter, 5-degree cutting edge and 1.5 mm wall thickness). The use of these thin, sharp-edged tubes has been shown to offer an acceptable method to obtain good quality specimens of low-plastic Fraser River silt for laboratory testing (Sanin and Wijewickreme, 2006a). The samples were shipped to the laboratory in secured light-weight packing with instructions to minimize disturbance, and they were carefully stored in a moisture-controlled room until the time of sample extrusion and preparation for testing. Gradation curves of the material included in this study are presented in Figure 1, along with some key physical characteristics given in Table 1.

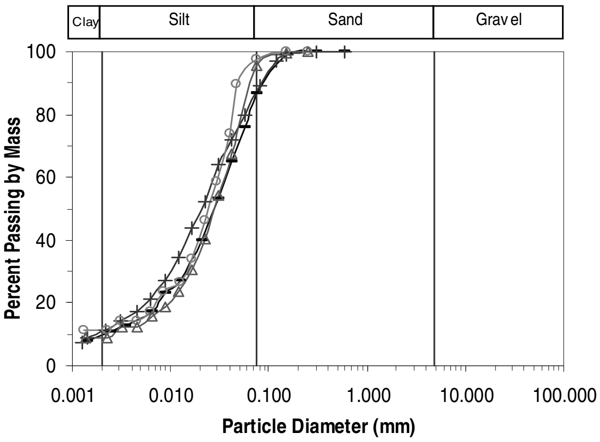

Figure 1. Grain size distribution of Fraser River delta silt at different depths.

Table 1. Index properties of Fraser River delta silt

Index Property	Values
Water content, w_c (%)	38.8
Liquid limit, LL (%)	34.9
Plastic limit, PL (%)	30.5
Plasticity Index, PI	4.4
Liquidity Index, I_w	1.4
% of particles < 0.002mm	10%
% of particles > 0.075mm	5%
Unified soil classification	ML
Specific gravity, G_s	2.69

The device used for DSS testing is NGI-type (Bjerrum and Landva 1966), and it allows the testing of a specimen having a diameter of ~70 mm and height of 20 to 25 mm. In DSS tests, as an alternative to suspending the drainage of a saturated specimen, a constant volume condition can be enforced even in a dry soil by constraining the specimen boundaries (diameter and height) against changes. The specimen diameter is constrained against lateral strain using a steel-wire reinforced rubber membrane, and the height constraint is obtained by clamping the top and bottom loading caps against vertical movement. It has been shown that the decrease (or increase) of vertical stress in a constant volume DSS test is essentially equal to the increase (or decrease) of pore water pressure in an undrained DSS test where the near constant volume condition is maintained by not allowing the mass of pore water to change (Finn et al. 1978; Dyvik et al. 1987).

After extrusion from the sample tube, the specimens of the natural undisturbed silt were secured in the DSS device with assistance from a polished-stainless steel sharpened-edge cutting-ring. After sample set-up, the specimens were loaded to the desired vertical effective stress. Reconstituted DSS specimens were prepared by forming a thick slurry of Fraser River silt mixed with de-air water and left under vacuum for at least 24 hours, while stirring occasionally to eliminate trapped air bubbles and obtain a relatively saturated slurry. The slurry was carefully transferred, using a spoon, into the specimen mould containing the reinforced-rubber DSS membrane. Since the material was placed in a slurry state, care was exercised to consolidate the reconstituted specimens in several stages of vertical loading to avoid loss of material due to squeezing. All specimens, after application of the final vertical stress, were left for consolidation for a period of 24 hours prior to commencement of shearing.

Data from monotonic DSS tests conducted on specimens initially consolidated to different levels of effective vertical confining stress (σ'_{vo}) between 100 to 400 kPa are examined herein. The results from one-dimensional consolidation testing of the undisturbed tube samples indicated a preconsolidation pressure of about 85 kPa for the in situ silt at the sampled location. As such, laboratory consolidation of DSS specimens to σ'_{vo} levels above 100 kPa assured that all the tests conducted on specimens prepared from undisturbed tube samples would be in a normally consolidated state prior to shear testing. After consolidation, all monotonic constant volume DSS tests were conducted at a horizontal shear strain rate of 10% per hour.

3 TEST RESULTS

The monotonic loading stress-strain and excess pore water pressure responses derived from undisturbed specimens of Fraser River delta silt are compared with those from the reconstituted specimens of the same silt in Figure 2.

The excess pore water pressure development during shear indicates that the specimens of reconstituted soils consistently behave in a more contractive manner in comparison to the undisturbed specimens, for the tests herein conducted with the initial vertical effective confining pressure ranging between 100 to 400 kPa. In terms of stress-strain response, the reconstituted specimens exhibited a mild strain-softening response before regaining its shear resistance. This is in contrast to the undisturbed specimens where the stress-strain response was essentially strain-hardening under constant volume monotonic loading. In an overall sense, the reconstituted specimens displayed a generally weaker stress-strain response than those yielded by the undisturbed specimens.

The stress-path response arising from the same tests are presented in Figure 3. The phase transformation (where the behaviour changes from contractive to dilative) seems to occur at the same mobilized shear stress ratio (τ/σ'_{vo}) regardless of whether the tested specimen is reconstituted or undisturbed.

The void ratio, e_c, attained under a given initial consolidation stress (σ'_{vo}) for the undisturbed and reconstituted specimens are presented in Figure 4 using open symbols. The observed linear plots of e_c - log σ'_{vo} are as expected and in accord with the consolidation response typically observed for normally consolidated fine-grained soils. However, it is important to note that the undisturbed and reconstituted materials exhibited distinctly different e_c -log σ'_{vo} characteristics; for a given initial confining stress, the reconstituted specimens attained consistently lower values of e_c during initial one-dimensional consolidation compared to the e_c values realized by the undisturbed specimens.

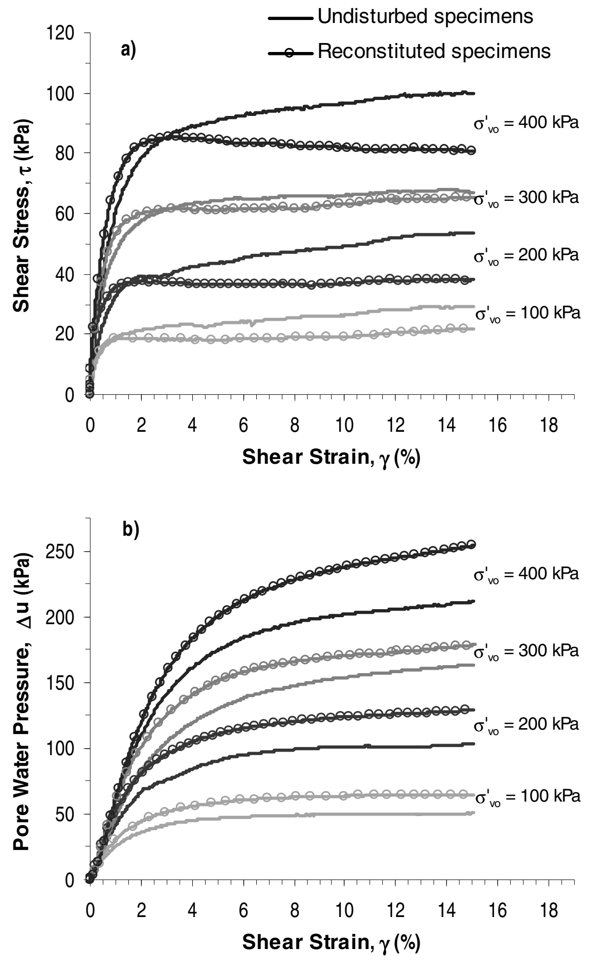

Figure 2. Response of undisturbed and reconstituted Fraser River silt under constant volume monotonic DSS loading.

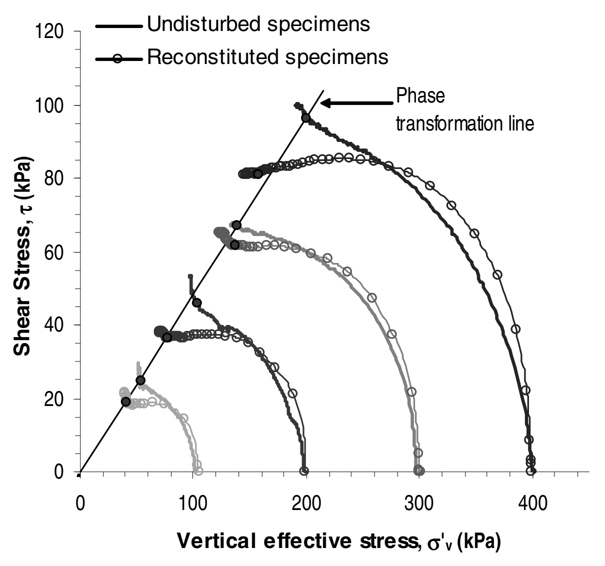

Figure 3. Stress paths during constant volume monotonic DSS loading of undisturbed and reconstituted Fraser River silt.

Since the above monotonic DSS tests were conducted at constant volume, the void ratio (e) does not change during the shearing process. However, since the vertical effective stress (σ'_v) changes with shear strain, it was considered of interest to assess the e-σ'_v state of the material after reaching relatively large strain levels. With this in mind, the location of e-σ'_v state of the specimens after reaching shear strain of ~15% is plotted in Figure 4 using solid symbols. It is of interest to note that, 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 that would generally parallel the corresponding e_c - log σ'_{vo} line depicting the initial consolidation response (i.e., data points with open symbols).

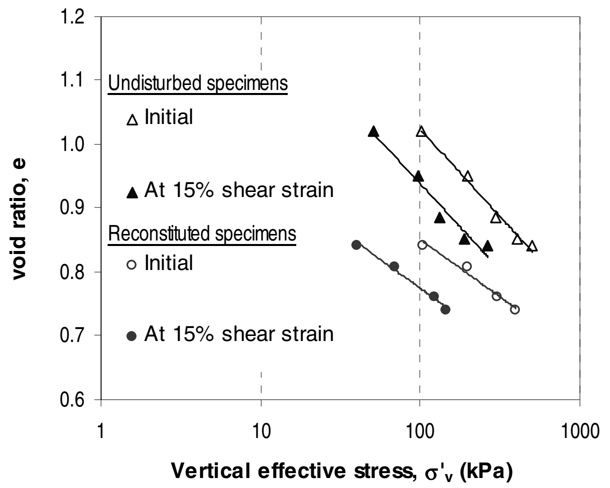

Figure 4. e-log σ'_v curves for undisturbed and reconstituted specimens of Fraser River silt.

4 SUMMARY AND DISCUSSION

The constant-volume monotonic shear response of low-plastic, normally consolidated fine-grained natural silt (Fraser River silt) was examined using data from monotonic direct simple shear DSS tests. The intent was to compare the monotonic shear response of undisturbed specimens versus reconstituted specimens of the same material tested under different consolidation stress conditions.

For the initial vertical effective confining pressure range between 100 to 400 kPa investigated herein, the tendency for volume change observed from specimens of reconstituted low plastic Fraser River silt (despite having a looser density under identical consolidation stress conditions) was consistently more contractive compared to that observed from the specimens of counterpart undisturbed material. This contractive response was also reflected in the stress-strain response, where the reconstituted specimens experienced a mild strain-softening response before regaining its shear resistance in contrast to the undisturbed specimens where the stress-strain response was essentially strain-hardening. 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. Similar observations have been made on low plastic silt by Wijewickreme and Sanin (2008) mainly based on testing conducted under constant volume cyclic loading conditions.

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 characteristics essentially as two unrelated different materials, in spite of their identical mineralogical origin and grain size.

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 behavior of low plastic silt; the differences can be reasonably attributed to considerations such as the difference in particle structure (soil fabric) and the age which 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.

The behavioural contrast between the undisturbed and the reconstituted specimens observable in the specimen initially consolidated to 400 kPa suggests that the original structure of the undisturbed specimens seem to prevail even after consolidating the material to a confining stress level significantly higher than the estimated preconsolidation stress for the natural soil.

Due to the costs and difficulties associated with field "undisturbed sampling", there is a tendency to use reconstituted specimens for assessing the shear response of silts. The validity of this approach relies on the assumption that reconstituted laboratory specimens would reasonably represent the field material as long as the e_c-σ'_{vo} conditions are suitably matched. The findings from the present study indicate that such an approach of using reconstituted specimens does not necessarily reflect the characteristics of natural material, and it would likely generate overly conservative parameters for design purposes. It appears that there is merit in obtaining undisturbed samples to assess the field behavior of natural fine-grained silts such as Fraser River silt.

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