Observations on the effect of strain rate and loading rate on monotonic and cyclic direct simple shear response of reconstituted Fraser River silts

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ABSTRACT

The influence of the shearing rate on the response of sand as well as clay has been investigated and well-documented; however, such investigations on silt, especially the studies on the effects of strain/loading rates in the available literature is very limited. With this background, a series of constant-volume direct simple shear tests were conducted on reconstituted Fraser River silt with the objective of examining the effects of different strain and shear loading rates. This paper presents the results of strain-controlled monotonic direct simple shear tests with varying strain rates of 2%, 10% and 150% shear strain per hour; constant-amplitude sinusoidal stress-controlled cyclic shearing with loading cycle periods of 5 s, 10 s, 100 s, and 1000 s were also conducted. The experimental results indicate no significant variations in the peak shear resistance due to the different strain rate selected in monotonic shearing. However, increasing cyclic shear resistance tendency could be observed for increasing loading frequency (decreasing loading period). The observed characteristics on pore-water pressure development, shear strain accumulation, shear stiffness reduction/degradation and damping are presented and discussed with respect to the strain and loading rates.

RÉSUMÉ

L'influence du taux de cisaillement sur la réponse du sable ainsi que sur l'argile a été étudiée et bien rapportée. Cependant, ces études sur le limon, les études sur les effets des taux de contrainte / charge dans la littérature disponible sont très limitées. Afin de contribuer à améliorer ces connaissances, une série d’essais de cisaillement simple directe à volume constant ont été menées sur des spécimens de limon reconstitués du Fraser, dans l’intention de prendre en compte les effets de différentes vitesses de déformation et de charge de cisaillement. Cet article présente les résultats d'essais de cisaillement simple, direct, monotones et contrôlés par contrainte, avec différentes vitesses de contrainte, telles que des contraintes de cisaillement de 2%, 10% et 150% par heure; un cisaillement cyclique contrôlé par une contrainte sinusoïdale d'amplitude constante avec des périodes de cycle de chargement de 5, 10, 100 et 1000. Les résultats expérimentaux indiquent qu’aucune variation significative de la résistance maximale au cisaillement n’est due aux différentes souches classées dans le cisaillement monotone. Cependant, une tendance croissante à la résistance au cisaillement cyclique a pu être observée pour une fréquence de charge croissante (période de charge décroissante).

1 INTRODUCTION

Many researchers (Lee et al. 1969; Tatsuoka et al. 1999; and Yamamuro et al. 2011) have experimentally investigated the response of sands and have reported that there is a general tendency of increasing shear strength with increasing strain rates and loading rates. Lee et al. (1969) have mentioned that (a) dilatancy increases at low confining pressure as the strain rate increases; (b) particle crushing probably contributes to an increase in strength at higher rates of strain; (c) effect of sliding friction on the shear strength as increasing strain rate is uncertain. Further, Yamamuro et al. (2011) have also observed increasing volumetric dilations, shear secant modulus, maximum principal stress ratio with increasing strain rates. For the case of clay, Katti et al (2003) reported that the undrained shear response of clay has shown an apparent over-consolidation behavior with increasing strain rates. Many experimental studies (Richardson and Whitman 1963; Lefebvre and LeBoeuf 1987; Zergoun and Vaid 1994; Gratchev and Sassa, 2015; Scaringi and Di Maio 2016) have also indicated the increase in shear strength of clay as the strain rate increases. During cyclic triaxial tests, the observed variations of the undrained shear strength with strain rates by Lefebvre and LeBoeuf (1987) were about 7-14% per log cycle

However, such experimental investigations on the response of silts with respect to strain rate are very limited in the literature. With the intension to bridge the existing knowledge gap due to the lack of available good quality data, a series of constant-volume direct simple shear tests were conducted on reconstituted Fraser River silt with different loading and strain rates. Both monotonic and cyclic shear loading responses of reconstituted silt specimens are presented and compared with respect to the variation of strain and loading rates; this paper presents the key observations arising from this study.

2 SOIL TESTED AND LABORATORY TEST PROGRAM

Natural silt excavated from the south bank of the Fraser River adjacent to the Port Mann bridge in the Lower Mainland in British Columbia, Canada (called Fraser River silt hereinafter) was utilized as the soil material for the current testing. The silt was oven dried and then sieved to remove the fine sand potion (i.e., removed the fraction coarser than 75 μm). The non-plastic silt (after processing) has about 20 % of clay size particles (finer than 2 μm) and the mean particle size (d_{50}) is about 18 μm.

2.1 Specimen Preparation

Direct simple shear (DSS) device at University of British Columbia was used for the testing herein. The UBC-DSS device is a modified Marshall-Silver-NGI (Norwegian Geotechnical Institute) type device (Silver and Seed, 1971) which uses a cylindrical soil specimen and follows the DSS testing methodology as described by Bjerrum and Landva (1966). The device 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 soil specimens for testing were prepared by slurry deposition method, and more details are available in Soysa (2015).

2.2 Constant-volume Monotonic and Cyclic Direct Simple Shear

In the DSS device, the test specimen is laterally confined by the wire-reinforced membrane, and it enforces an essentially constant cross-sectional area by preventing the specimen from localized lateral straining during consolidation and shear deformation. A constant-volume condition can be enforced by clamping the top and bottom loading platens of the test 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 (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.

All the test specimens were consolidated to a nominal vertical effective consolidation stress (σ'_{vc}) of about 100 kPa. The monotonic shear load was applied via a constant displacement rate. In this test series (presented in Table 1), the monotonic tests were conducted with various shear strain (γ) rates of about 2%, 10%, and 150% per hour. For cyclic shear loading, the specimens were subjected to symmetrical sinusoidal cycles of loadings where the constant cyclic stress ratio (CSR = τ_{cyc}/σ'_{vc}) amplitude of about 0.14 with different cyclic loading periods of 5 s, 10 s, 100 s, and 1000 s (i.e., the corresponding frequencies of 0.2 Hz, 0.1 Hz, 0.01 Hz and 0.001 Hz).

2.3 Test Program

Effects of the strain and loading rates on the shear loading response of reconstituted Fraser River silt was investigated constant-volume DSS tests with three different strain rates (controlled by constant displacement rates) and four different cyclic loading periods (constant amplitude sinusoidal shear loading waves); summary of the strain rates and loading rates are listed in Table 1. The post-consolidated void ratios (e_c) of the reconstituted silt specimens in relation the applied σ'_{vc} are also listed in Table 1. For the ease of comparison, the figures presenting shear stress-strain and stress-path response, the shear and vertical effective stress values were normalized by σ'_{vc} considering the slight variations of σ'_{vc} for the different specimens listed in Table 1.

Table 1. Summary of test program

Test ID	Rate	e_c	σ'_{vc} (kPa)
RS-100-M2	2 % γ / h	0.72	96
RS-100-M10	10 % γ / h	0.74	99
RS-100-M150	150 % γ / h	0.76	97
RS-14-05	5s (0.2Hz)	0.77	98
RS-14-10	10s (0.1Hz)	0.74	99
RS-14-100	100s (0.01Hz)	0.77	98
RS-14-1000	1000s (0.001Hz)	0.7	98

The current guidelines for selecting appropriate strain rates for the laboratory shear tests on fine-grained soils is based on the recommendations provided by Bishop and Henkel (1962) and Germaine and Ladd (1988) comprise:

(i) the estimation of t_{100} (time for 100% consolidation) as shown in Figure 1;
(ii) interpretation of c_v (coefficient of consolidation) based on the t_{100} and drainage condition during the consolidation phase (where h = half the height of the specimen for the case of double drainage);

$$c_v = \pi\, h^2/4t_{100} \quad [1]$$

(iii) estimation of time t_s to significant stress measurement in undrained test or time to failure in drained test;

$$t_s = 2t_{100} \quad [2]$$

(iv) experience based assumption for the shear strain at the failure / peak shear resistance (γ_f)
(v) estimation of appropriate shear strain rate undrain test

$$\dot{\gamma} = \gamma_f/t_s \quad [3]$$

The value of h for the specimen being 10 mm, the value of c_v from Equation [1] was estimated to be 91 mm^2/min; whereas, the estimated t_s from Equation [2] equals to 1.7 min. When shear strain at the peak shear resistance is assumed to be 2%, appropriate strain rate found to be about 70% per hour for the reconstituted Fraser River silt in undrained constant-volume monotonic DSS tests.

It should be noted that the above procedure to estimate appropriate strain rates are based on the experimental data based on clays and the method also comprises of many estimated and assumed values. Therefore, in order to evaluate the effects on the strain rate on the shear loading response, it was considered to conduct tests with significantly lower (as well as greater) than the estimated value of 70% shear strain per hour. Thus, three monotonic DSS tests were performed with shear strain rate 2 %, 10 %, and 150 % per hour.

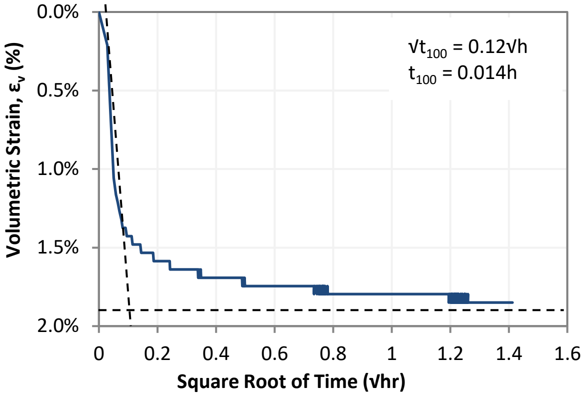

Figure 1. Estimation of t_{100} (according to Bishop & Henkel, 1962) from a typical consolidation curve for reconstituted silt specimen from 50 kPa to 100 kPa consolidation stress increment in the DSS test device

For the case of cyclic loading on clay, Zergoun (1991) recommended: (i) strain controlled loading for higher cyclic stress levels, as stress controlled loading could be generally accompanied by creep deformations; (ii) stress controlled cyclic loading for lower stress levels where creep deformations are minimal; and (iii) stress controlled loading initiation for intermediate cyclic stress levels and then switching to strain controlled conditions to control the development of increasingly greater strain with increasing number of loading cycles. Since these levels of lower, intermediate and higher stress regimes are dependent on the material, they needed to be identified based on the material shear loading response.

For the initial investigation on the cyclic shear loading rate on the reconstituted silt, CSR of 0.14 was selected based on the experience and previous observations on the strain accumulation during cyclic DSS loading for both relatively undisturbed and reconstituted silt specimens - with the assumption that creep deformations would not occur at slower loading rates. Hence, stress controlled with symmetrical sinusoidal wave type loading cycles, having a constant CSR of 0.14 with four different loading periods of 5 s, 10 s, 100 s, and 1000 s were selected for this test program.

3 MONOTONIC SHEAR LOADING RESPONSE

The normalized shear stress-strain and normalized stress path responses obtained for reconstituted Fraser River silt specimens with three different strain rates of 2%, 10% and 150% per hour from constant-volume monotonic DSS tests are presented Figure 2. Despite the three different strain rates in monotonic shearing, the initial peak shear resistance occurred at a shear strain level of about 2 %. Beyond the observed initial peak in shear resistance, similar strain softening type responses can be observed in all three stress-strain plots up to shear strain of about 5 %, which was then followed by very similar strain hardening type response till shear strain of about 10 %. Further increase of shear strain led to a decrease in shear resistance of the specimen with a 2% shear strain per hour; whereas shear resistance of other two specimens slightly increase, if not remain almost same till the larger strain level. In essence, the stress-strain plots suggest that significant differences in terms of shear resistance cannot be observed for the three selected strain rates in the initial part of the stress strain response (up to 10 % of shear strain).

In spite of this, the normalized stress-paths shown in Figure 2 indicate a dilative tendency in the specimen with greatest shear strain rate in the study (150 % shear strain per hour) during the initial shearing; whereas, the other two specimens exhibiting similar contractive tendency. This is further shown in the Figure 3, where normalized shear stress-strain and excess pore-water responses for the initial shearing up to 2% shear strain are presented. A negative level of pore-water pressure can be noted up until about 0.3% shear strain in the specimen with fastest stain rate, in which continuously lesser excess pore-water pressures can be noted with respect to other two counterpart specimens; in turn, resulting in a slightly greater shear resistance.

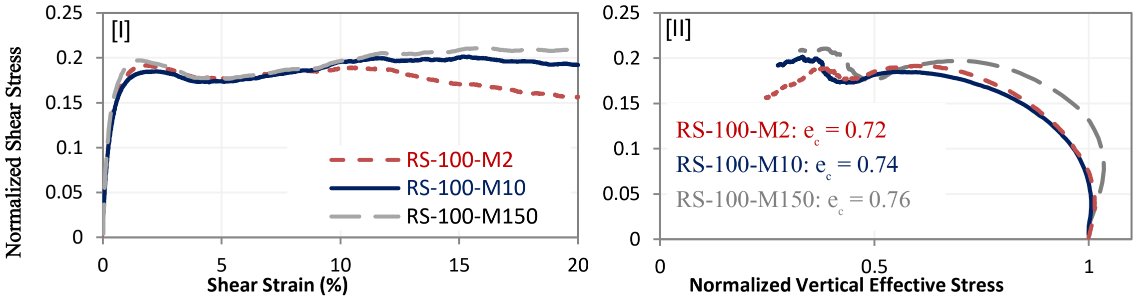

Figure 2. Normalized shear stress-strain [I] and normalized stress path [II] responses from constant-volume monotonic DSS tests on reconstituted Fraser River silt specimens with three different strain rates of 2%, 10% and 150% per hour

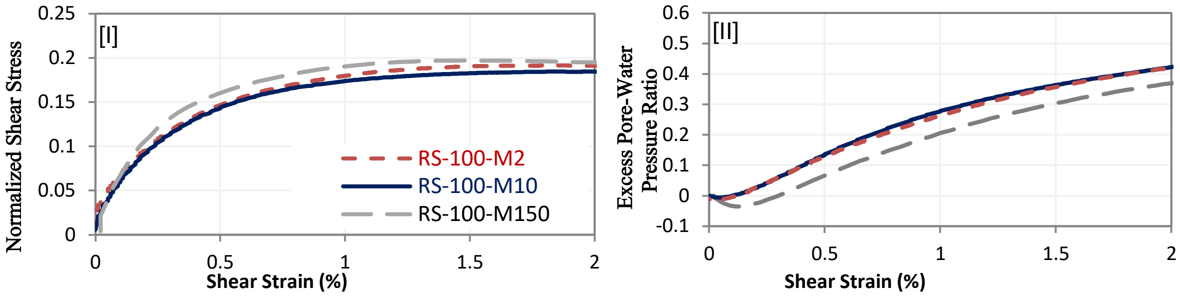

Figure 3. Normalized shear stress-strain [I] and excess pore-water pressure ratio [II] responses for initial strain development up to 2% during the constant-volume monotonic DSS tests on reconstituted Fraser River silt specimens with three different strain rates of 2%, 10% and 150% per hour

4 CYCLIC SHEAR LOADING RESPONSE

The normalized shear stress-strain and normalized stress path responses from constant-volume cyclic DSS tests on reconstituted Fraser River silt specimens with a CSR of about 0.14, at four different loading period of 5 s, 10 s, 100 s, and 1000 s are presented in Figure 4. Although relatively similar shear stress-strain response can be observed for the four cases of different loading periods, an increased level of shear strain can be notable in the specimen with slower loading rates (loading cycle periods with 100 s and 1000 s).

When normalized stress-path plots are carefully observed for the initial quarter of the first loading cycle, it can be seen that the dilative tendency is gradually decreased with increasing loading period. For example, both specimens with loading periods of 5 s and 10 s (comparatively faster loading), dilative tendency could be observed till the end of initial loading phase (first quarter of the first load cycle) and then exhibit the contractive tendency during unloading phase (second quarter of the first load cycle); whereas, in the specimens with loading periods of 100 s and 1000 s (slower loading), dilative tendency in the initial quarter of the first loading cycle are less prominent. The point in each normalized stress-path plot, where end of initial quarter of loading cycle (just prior to the start of second quarter of the first load cycle) is marked with a solid black dot for the clarity.

In general, the stress-path response of all the test specimens look similar “in terms of pattern” with the exhibited contractive and dilative tendencies during loading and unloading potions of cyclic shear stress, respectively. However, the response is found to be notably different when shear strain accumulation, excess pore-water pressure development (Figure 5) and shear modulus degradation (Figure 6) are considered.

The rate of shear strain accumulation and excess pore-water pressure development for the both specimens with cyclic loading periods 5 s and 10 s are found to be similar; this may be due to that the loading period for those two cases are not significantly different. However, the results shown in Figure 5 indicate a clear increasing trend for rate of shear strain accumulation and pore-water pressure development when the loading period is increased (by 10-fold and 100-fold). In other words, the longer the period of the loading cycle, lesser the number of loading cycles for the specimen to reach greater excess pore-water pressure ratio and higher shear strain.

The strain accumulation and pore-water pressure development contribute to the reduction of shear stiffness of silt; the shear stiffness (G) degradation over consecutive quarter cycles of loading is illustrated in Figure 6 [Note: the two shear moduli were computed based on the shear strain values as follows: γ(+) = shear strain corresponding to maximum shear stress experienced during loading on the positive side of the y-axis (i.e., first half of the loading cycle) and γ(-) = shear strain corresponding to minimum shear stress experienced during loading on the negative loading side of the y-axis (i.e., second half of the loading cycle). The resulting G values are identified as G(+) and G(-), respectively, in Figure 6.

Firstly, it can be clearly noted that higher loading periods contribute to greater rate of shear stiffness degradation. Secondly, the higher loading periods seems also contribute to decrease the computed shear stiffness for the very initial loading cycle. Finally, it is also notable that in most of the cases, values of |γ(-)| are greater than |γ(+)|, resulting G(+) to be greater than G(-). With increasing number of loading cycles, the difference between |γ(+)| and |γ(-)| increases. Further, it is also visible that higher the loading period, higher would be the difference between |γ(+)| and |γ(-)|. This may be some evidence on effect of possible deformation due to creep.

The positive section of the first normalized shear stress-strain loop obtained for the reconstituted Fraser River silt specimens with four different loading periods of 5 s, 10 s, 100 s, and 1000 s are compared and presented in Figure 7. The specimens that were subjected to loading period with 100 s and 1000 s exhibit comparatively greater shear strain in the first half of the loading cycles than that observed for rest of two specimens with lower loading periods. It would be difficult to differentiate the effects of loading-rate-induced and creep-induced deformations; however, in sinusoidal loading waves, rate of stress increments/decrements at the peak and trough are lower than the other section of the loading wave, thus allowing

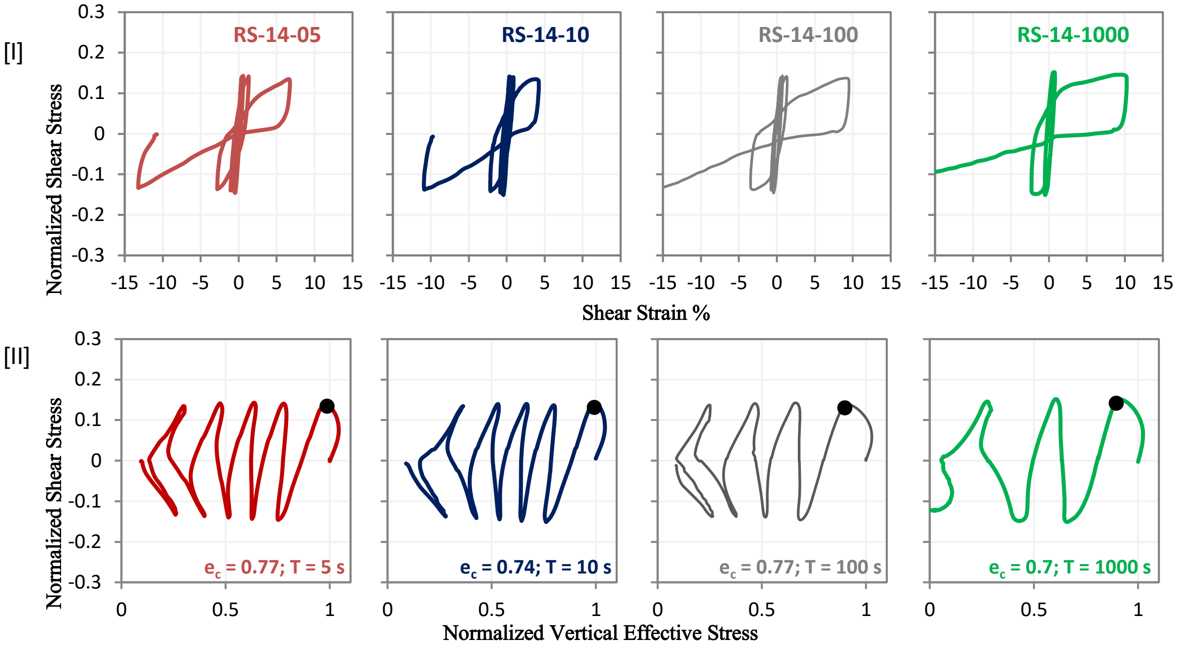

Figure 4. Normalized shear stress-strain [I] and normalized stress path [II] responses from constant-volume cyclic DSS tests on reconstituted Fraser River silt specimens with a CSR of about 0.14, at four different loading periods of 5 s, 10 s, 100 s, and 1000 s.

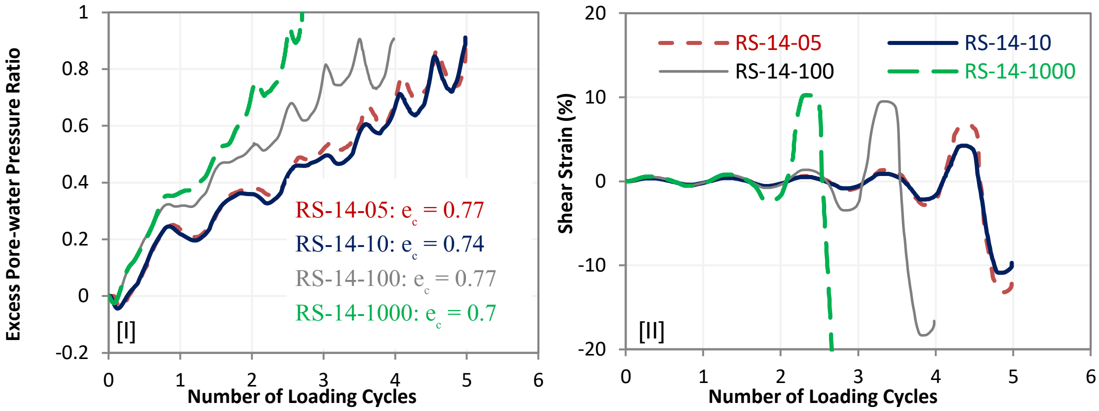

Figure 5. Development of excess pore-water pressure [I] and accumulation of cyclic shear strain [II] with respect to number of loading cycles during the constant-volume cyclic DSS tests on reconstituted Fraser River silt specimens with a CSR of about 0.14, at four different loading periods of 5 s, 10 s, 100 s, and 1000 s.

more opportunity to possible creep induced deformations. As expected, it was observed greater level of strains occurs specially at the peak and the trough of the sinusoidal waves, when the loading period is higher as 100 s and 1000 s.

The first normalized shear stress-strain loop obtained from the reconstituted Fraser River silt specimens with four different loading periods of 5 s, 10 s, 100 s, and 1000 s are presented in Figure 8. These loops can be studied in an approximate way with respect to hysteresis characteristics to assess the variation of damping of silt specimens under different loading periods. The stress-strain loops shown in Figure 8 suggest that the area enveloped inside the hysteresis loop, A_L, seem to increase with increasing loading period.

The equivalent viscous damping factor, D, for the silt can be estimated from the energy dissipated and stored ratio during the cyclic loading cycle in according to the Equation [4].

$$D = \{1/4\pi\}\{A_L/\,A_T\} \quad [4]$$

As shown in Figure 8, the computed values suggest that higher loading periods resulted in greater D. It also suggests the loading frequency dependency of silt behavior, as the same reconstituted material exhibit different strain accumulation and damping characteristics, when they were subjected to cyclic loading with different frequencies (when sheared under a similar loading amplitude of about 0.14).

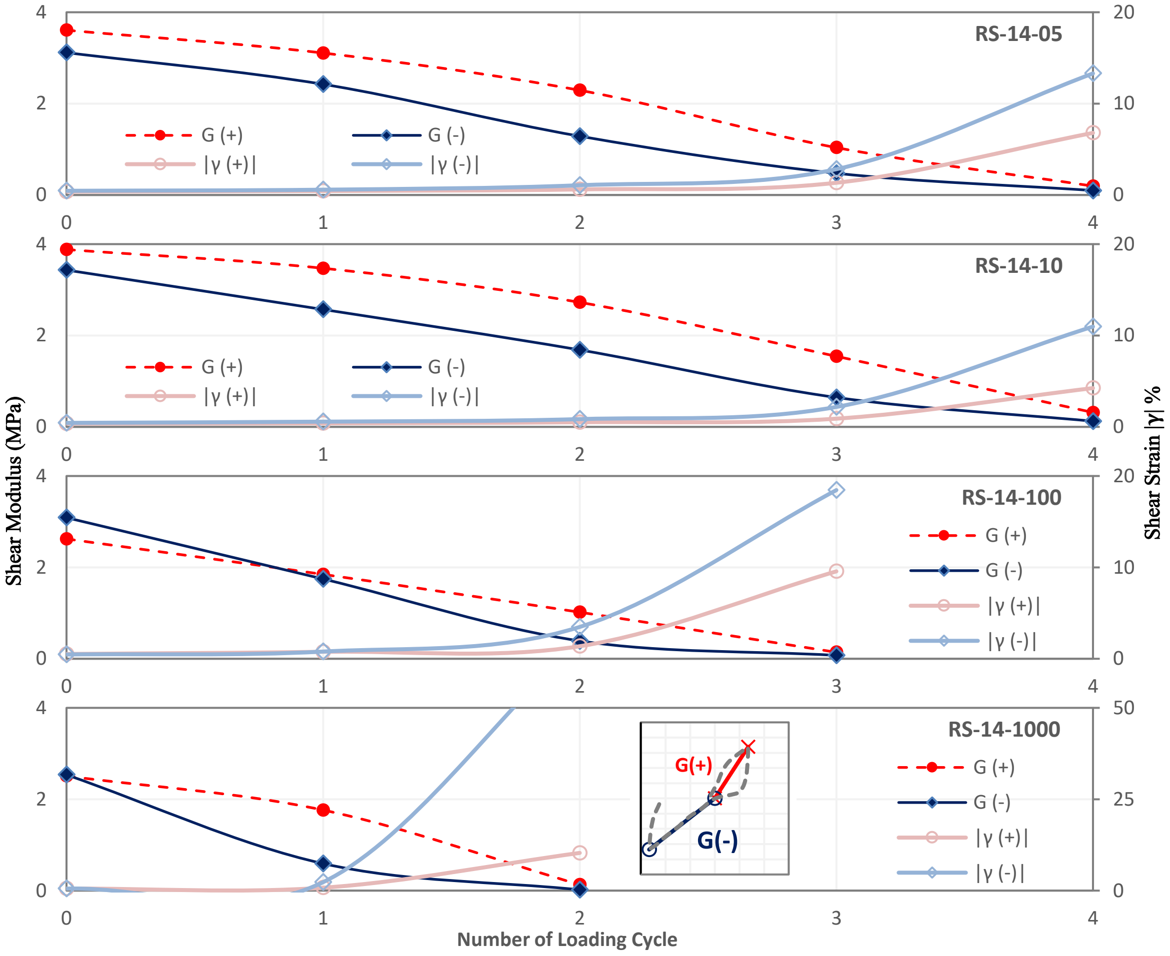

Figure 6. Shear Modulus degradation during the constant-volume cyclic DSS tests on reconstituted Fraser River silt specimens with a CSR of about 0.14, at four different loading periods of 5 s, 10 s, 100 s, and 1000 s.

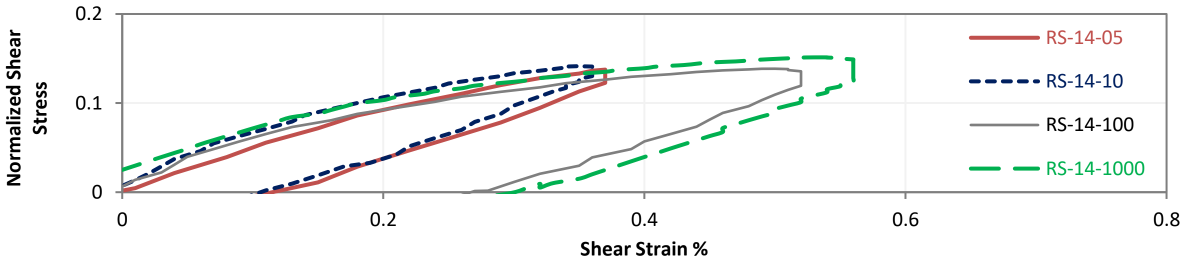

Figure 7. A comparison of the positive section of the first normalized shear stress-strain loop obtained for the reconstituted Fraser River silt specimens during the constant-volume cyclic DSS tests with a CSR of about 0.14, at four different loading periods of 5 s, 10 s, 100 s, and 1000 s

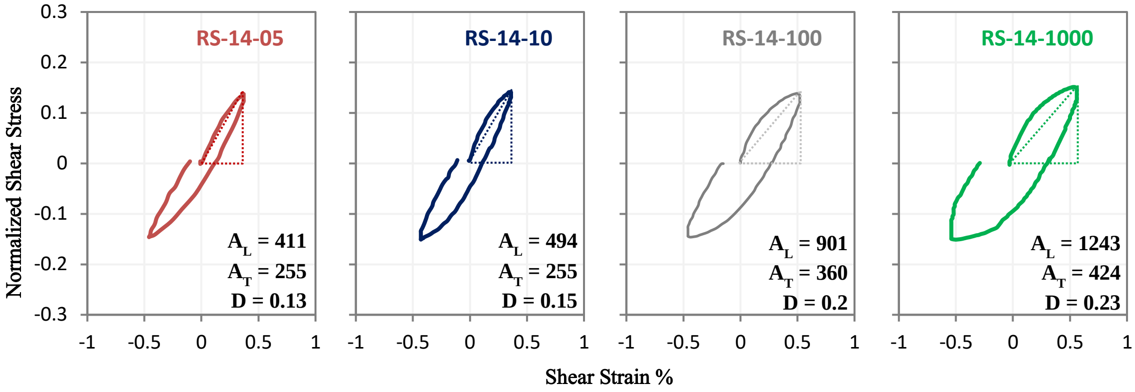

Figure 8. A comparison of the first normalized shear stress-strain loop obtained for the reconstituted Fraser River silt specimens during the constant-volume cyclic DSS tests with a CSR of about 0.14, at four different loading periods of 5 s, 10 s, 100 s, and 1000 s. [A_L – Area of the stress-strain loop, A_T = Area of the triangle, D = Equivalent viscous damping factor derived from A_L and A_T]

5. SUMMARY AND CONCLUSIONS

Strain-controlled, monotonic, constant-volume direct simple shear tests with varying strain rates (of 2%, 10% and 150% shear strain per hour) and constant-amplitude sinusoidal cyclic shearing (with loading cycle periods of 5 s, 10 s, 100 s, and 1000 s) were performed on reconstituted non-plastic Fraser River silt. The following key observations and/or conclusions can be made on the examination of experimental results;

- A shear strain rate not exceeding about 70% per hour were estimated suitable for monotonic DSS testing of reconstituted Fraser River silt, based on the Bishop and Henkel (1962) and Germaine and Ladd (1988) approaches that have been developed for clayey soils.
- Monotonic tests performed at shear strain rates below 70% per hour exhibited similar shear loading response during the initial shearing stage. This is in contrast to the observations from a monotonic test conducted at 150% shear strain per hour, where significant negative pore-water pressure development at the initial shearing stage with a comparatively higher shear strength (with respect to the counterpart specimens with relatively slower strain rates) were noted.
- The cyclic DSS tests on Fraser River silt with different loading periods such as 5 s, 10 s, 100 s, 1000 s with a constant cyclic stress ratio of 0.14, exhibited higher rate of excess pore-water pressure development and shear strain accumulation with increasing cyclic loading period.
- Although it is very difficult to distinguish the shear strain development effects due to loading period from creep-induced strain, the results seem to indicate possible creep-induced strain specially at higher cyclic loading periods
- The shear stiffness degradation and damping characteristics observed by examining the stress-strain loops reveal that the shear loading response of reconstituted Fraser River silt is loading frequency dependent – e.g., higher frequency of cyclic loading results in stronger undrained cyclic shear resistance.

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