Experiment setup for simple shear tests in a triaxial cell: T_xSS

Mohamed Chekired & Réjean Lemire
Hydro-Québec, Montréal, Québec, Canada

Mourad Karray & Mahmoud N. Hussien
Department of Civil Engineering, Faculty of Engineering, Sherbrooke University, Sherbrooke, QC, Canada

ABSTRACT
This paper documents the development of a new combined triaxial simple shear (T_xSS) apparatus. The T_xSS system consists of a simple shear apparatus incorporated in a triaxial cell for the measurements of static and dynamic characteristics of soil samples. A general description as well as some applications and advantages of the TxSS systems over the traditional apparatus are given in this paper. The key application of T_xSS is the evaluation of liquefaction potential of soil under regular or irregular excitations. Sample results in terms of static and dynamic characteristics obtained using the T_xSS device on different cohesive and cohesionless soil samples are presented to illustrate its capabilities, and they are successfully compared to those obtained using reliable design charts available in the literature as well as those from rigorous numerical analyses using the computer code FLAC.

Keywords: T_xSS , DSS, triaxial, simple shear, liquefaction.

RÉSUMÉ
Cet article documente le développement d'un nouvel appareil de cisaillement simple triaxial (TxSS) combiné. Le système TxSS se compose d'un appareil de cisaillement simple incorporé dans une cellule triaxiale pour la mesure des caractéristiques statiques et dynamiques des échantillons de sol. Une description générale de l'appareil est des diverses possibilités qu'il peut fournir seront présentées. L'application clé de TxSS est l'évaluation du potentiel de liquéfaction du sol sous des sollicitations uniformes ou non uniformes. Les résultats des échantillons, en termes de caractéristiques statiques et dynamiques, obtenus en utilisant le dispositif TxSS sur différents échantillons de sol cohérent et granulaires sont présentés pour illustrer ses capacités. Ces résultats sont comparés à ceux obtenus en utilisant des modèles de comportement disponibles dans la littérature ainsi qu'à ceux d'analyses numériques en utilisant le code informatique FLAC.

1 INTRODUCTION

It has been widely recognized among researchers and design engineers that laboratory tests that replicate field loading conditions as closely as possible should be performed to estimate the relevant geotechnical parameters in a design situation (e.g., Dyvik et al. 1987; Boulanger et al. 1993). A wide variety of laboratory apparatuses are available, each with different merits and limitations with respect to different problems. For example, in conventional triaxial compression and extension tests, the plane strain tests, and the true triaxial tests, only normal stresses are controlled and measured. Triaxial equipment cannot duplicate rotations of the principal stress directions during shearing that are usually encountered in the field under earthquake loadings. In fact, conventional triaxial tests allow only for an instantaneous rotation through 90^o of the principal stress directions. The direct simple shear (DSS) test apparatuses are often superior to triaxial test devices as they allow for a smooth and continuous rotation of the principal stress directions during shearing. A major limitation of the DSS test appears to be the practical difficulty of imposing a uniform normal and shear stress field along the plane of deformation. The DSS devices do not allow for the development of complementary shear stresses on the vertical sides normal to the plane of deformation, and consequently the shear and normal stresses must be non-uniform along the plane of deformation (Airey et al. 1985). Moreover, many in situ conditions of soils are three-dimensional in nature and cannot always be simplified to the uni-directional loading conditions that are modelled in the DSS test apparatuses (e.g., Franke et al. 1979; Dyvik et al. 1987; Boulanger et al. 1993; Duku et al. 2007).

To provide reliable results, the used device should meet certain principle requirements including (e.g., Boulanger et al. 1993; Sadrekarimi and Olson 2009): (i) the ease of mounting reconstituted and undisturbed soil samples; (ii) the facility to consolidate a soil specimen under drained conditions to a desirable confining pressure, and then sheared under either drained or undrained conditions; (iii) the opportunity to apply back pressure to ensure full saturation of the specimen and the direct measurement of the pore water pressure during the undrained shear test; (iv) the ability to rotate principle stresses of the tested specimen during shearing; and (v) the ability to utilize a sample large enough to develop a well-defined failure zone.

In an attempt to make consummate investigations (i.e., obtain high quality experimental test data) of the static and dynamic characteristics of soil samples in a triaxial condition, a new combined triaxial simple shear (T_xSS) apparatus was designed and constructed to achieve simple shear stressing on a soil sample in a triaxial chamber. The device is operated by an electric system which is capable of varying both shearing and confining stresses on a cylindrical soil specimen either monotonically or cyclically at different stress amplitudes and frequencies up to 10 Hz. The apparatus also offers the opportunity to apply regular and irregular cyclic strain or stress on the soil sample. The T_xSS can be simply reduced to the DSS applying using stacks of annular plates to laterally support the soil specimen or to the conventional triaxial test if there is no shear loading applied. A general description as well as some advantages and applications of the developed TxSS systems are given in the subsequent sections. Sample results in terms of static and dynamic characteristics obtained using the T_xSS device on different cohesive and cohesionless soil samples are presented to illustrate its capabilities, and they are compared to those obtained using reliable design charts available in the literature as well as those from rigorous numerical analyses using the computer code FLAC (Itasca 2010).

2 THE TRIAXIAL SIMPLE SHEAR (T_XSS) APPARATUS

The new triaxial simple shear (T_xSS) apparatus was designed and manufactured to permit the application of monotonic loading as well as both regular and irregular shear stresses or strains to soil materials. Figure 1 shows the general assembly of the T_xSS apparatus. The T_xSS device was designed to test cylindrical soil specimens with a diameter of 76 mm and varying heights in a triaxial pressure cell so that confining pressure and back pressure can be applied and monitored. The specimen is located between relatively rigid bottom and top caps and is typically confined by a rubber membrane. The bottom and top caps that contain fine porous stones provide a “frictional” surface while allowing for drainage into the porous stones. The specimen is first consolidated to a desirable confining stress, and then simple shear stress or strain is presumed to be imposed by displacing the specimen's top cap using the shear ram shown in Fig. 1, which is connected to a shaker mounted on a horizontal table. A computer-automated feedback-loop-controlled system provides an excellent control of stresses and strains. The T_xSS system permits testing soil samples with different heights under either drained or undrained conditions as well as the direct measurement of the pore water pressure generation during the undrained shear test. It also provides the opportunity for geotechnical engineers and researchers to test undisturbed and reconstituted soil samples under either isotropic or anisotropic loading conditions. Unlike the DSS test apparatus that limits the height of soil specimen to ensure uniform strain distribution in the specimen, the T_xSS tests can be performed for larger specimen heights and therefore well-defined failure zone such as that shown in Fig. 2a can be observed under unidirectional shearing in consistent with failure pattern soils experience in many practical geotechnical situations.

The T_xSS can be simply reduced to the DSS if the soil sample, prepared in a membrane-enclosed space, is surrounded by stacks of annular plates (rings) as shown in Fig. 2b, and a zero-confining pressure is applied. The

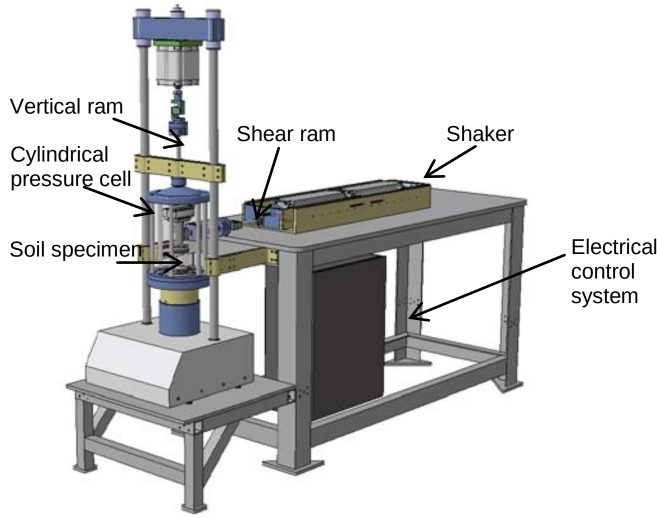


Figure 1. Schematic sketch of the triaxial simple shear (T_xSS) apparatus.

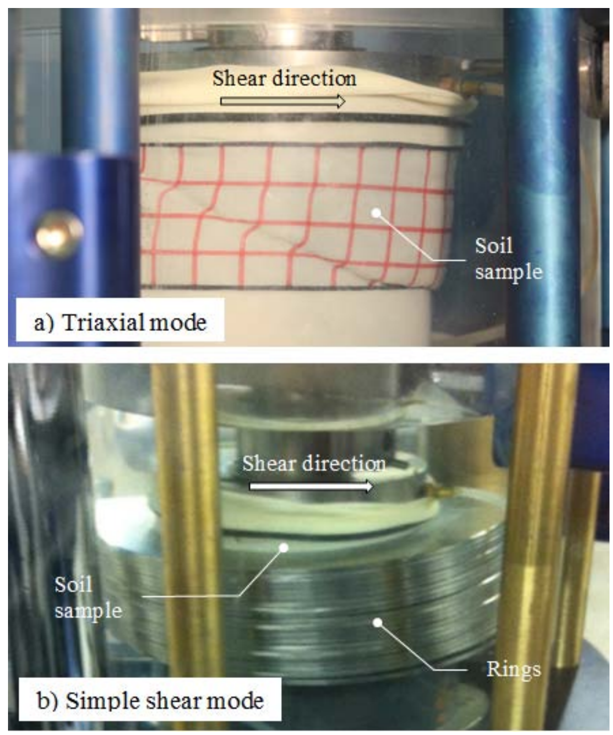


Figure 2. Different modes of shearing using the T_xSS .

T_xSS can also be reduced to the conventional triaxial test if there is no shear stress or strain is applied to the top cap.

3 TYPICAL T_XSS RESULTS AND INTERPRETATION

To evaluate the T_xSS device performance, we performed a series of monotonic and cyclic tests on different types of cohesive and cohesionless soils and the obtained results are then compared to those obtained using reliable design charts available in the literature as well as those from rigorous numerical analyses using the computer code FLAC (Itasca 2010).

3.1 Properties of the tested soils

The granular soils used in this study are Baie-Saint-Paul and Ottawa C-109 sands. The physical properties and the grain-size distribution curves of these soils are presented, respectively in Table 1 and Fig. 3. The cohesive soil used is soft post-glacial clays, of lacustrine, varved clay, coming from a site near Matagami (Olga site) in northwestern Québec. The basic physical properties of the clay used are presented in Table 2.

Table 1: Physical properties of the used granular soils.

Soil properties	Baie-Saint-Paul sand	Ottawa sand C-109
G_s	2.78	2.67
I_d %	55	12.5
e_{max}.	0.91	0.82
e_{min}.	0.598	0.5
e	0.7375	0.78
ρ_{max} (Kg/m^3)	1745.4	1780
ρ_{min} (Kg/m^3)	1457.4	1467
ρ (Kg/m^3)	1600	1500
C_u	2.25	1.75
C_c	1	1.016
D_{50}	0.15	0.4

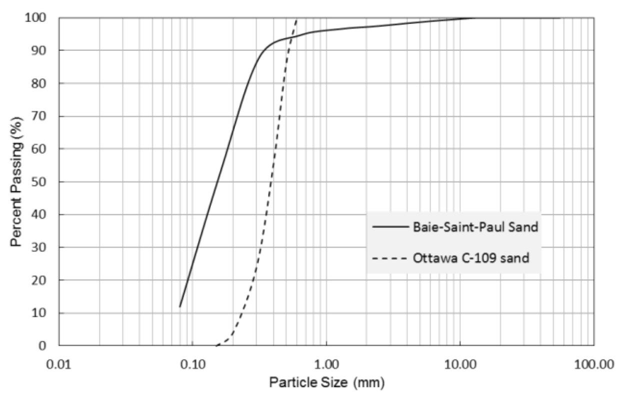


Figure 3. Grain-size distribution of the used sands.

Table 2: Physical properties of Olga clay (Lefebvre and LeBoeuf 1987).

Soil properties	Olga clay
Depth (m)	3.7 - 4.1
w %	90 - 93
w_l %	68
w_p %	28
I_p	40
I_l	1.55
< 2 μm %	90
σ'_p	78

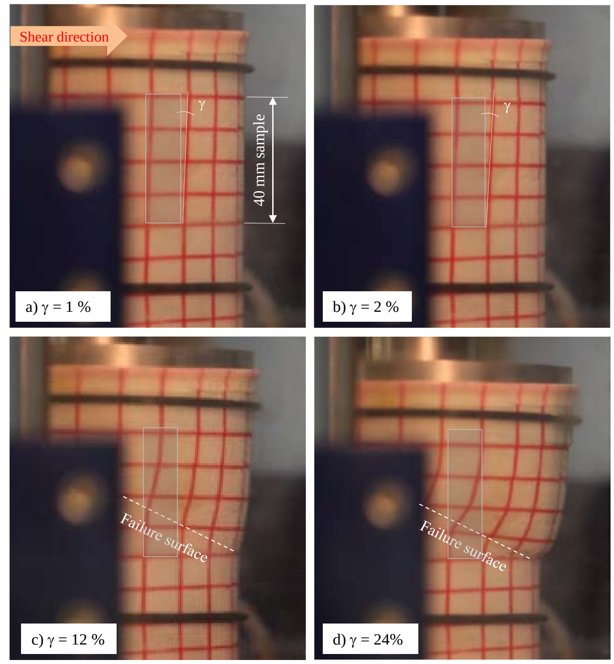


Figure 4. Shear distortions of a Bais-Saint-Paul specimen with a height of 40 mm under monotonic loading.

3.2 Monotonic loading test results

Examples of observed shear distortions of a specimen of Baie-Saint-Paul sand with a height of 40 mm tested in the T_xSS apparatus under monotonic loading at different strain levels are shown in Figs. 4a-d. For low strain level, γ = 1 and 2%, presented in Figs. 4a and 4b, the shear distortion conforms to that of a simple shear pattern. However, the increase in the applied shear strain, γ = 12 and 24%, presented in Figs. 4c and 4d, results in a significant change in the specimen shear mode to that observed in the conventional triaxial test. As shown in Figs. 4c and 4d, the diameter of the sample gradually increases due to the gradual shortening of the sample under the coupled effect of vertical loading and the excessive shearing. The middle of the sample bulges and a predominant failure surface is formed.

The measured shear stress-shear strain-pore pressure as well as vertical deformation of a saturated Baie-Saint-Paul soil specimen with initial relative density of 56 % tested at different initial confining pressures of 35, 75, 120 kPa are presented in Fig. 5. The shear stress-shear strain behavior of the tested Baie-Saint-Paul sand remains relatively brittle for all confining pressures adopted. The peak shear stress at failure increases with the applied confining pressure. The pore water pressure developed during shearing is significantly affected by the initial confining pressure. Post failure, however, Baie-Saint-Paul sand specimens tend to behave like de-structured soil with higher pore water pressure generated without any change in the loading rate. The vertical deformation observed in the tests reflects the dependency of the soil stiffness on the initial confining pressure especially at pre-

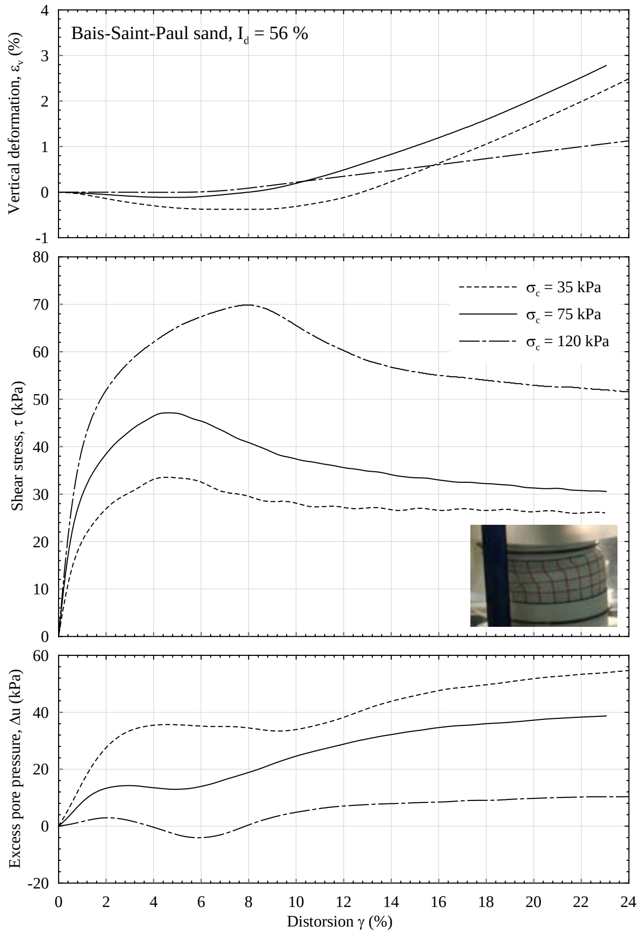
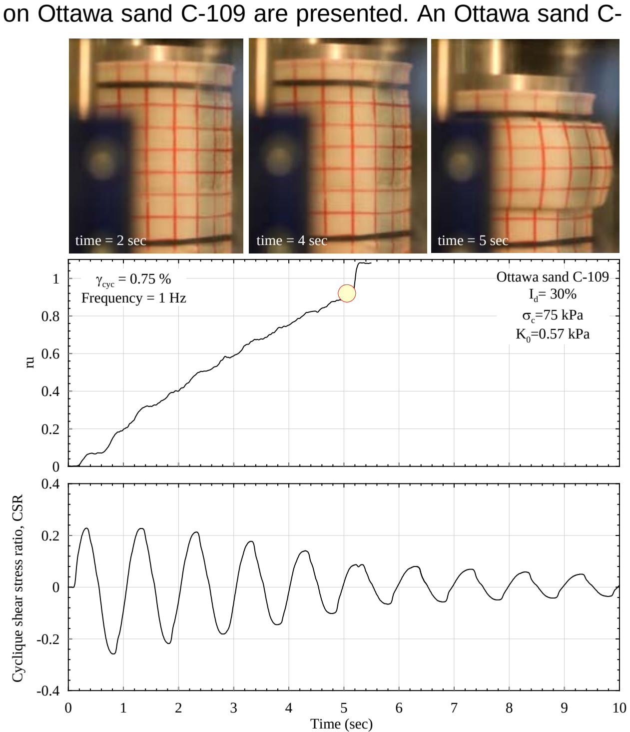


Figure 5. Vertical deformation, shear stress, and excess pore water pressure of a Baie-Saint-Paul specimen variation with shear distortion.

failure parts of the vertical deformation-shear distortion curves.

3.3 Cyclic loading response

In this section, typical results of a cyclic loading T_xSS test on Ottawa sand C-109 are presented. An Ottawa sand C-



109 specimen was consolidated to a relative density of about 50% under an initial vertical effective stress of 132 kPa and a lateral effective stress of 75 kPa (assumed K_o values of 0.57). Vertical and lateral stresses were simultaneously increased to these values. Once consolidation was completed, the vertical loading ram was locked off, and the drainage line was then closed and the specimen was ready for undrained cyclic shearing. The soil specimen is cyclically sheared under strain controlled condition with a maximum shear strain of 0.75% and a frequency of 1 Hz. as shown in Fig. 6. The CSR is defined as the amplitude of the soil cyclic shear stress ($\tau_{cyc.}$) divided by the initial effective confining stress (σ'_{co}). As shown in Fig. 6, a gradual drop of the CSR is observed associated with a gradual buildup/generation of the

Figure 6. Time histories of cyclic stress ratio and excess pore pressure of a Ottawa sand C-109 tested at a 75 kPa confining pressure and a relative density of 50% under cyclic strain γ= 0.75 % and a frequency = 1Hz.

excess pore pressure with the application of cyclic shear strain. It is worth noting that the tested soil is liquefied after 5 sec from the application of the cyclic shear strain. Initial liquefaction is defined in this study as the excess pore pressure, $r_u = u/\sigma'_{co}$, of 0.9, where u is the residual pore pressure. Shear distortions at different stages/times portrayed in the plot in the top of Fig. 6 confirms that the soil is completely liquefied at 5 sec.

3.4 Performance of the T_xSS against geotechnical design charts

Figure 7 shows cyclic stress ratio (CSR)-strain response of three T_xSS tests conducted on Ottawa C-109 sand tested at 30 kPa confining pressure and relative density of 30% at γ_{cyc} values of 0.09%, 0.2%, and 0.3% and a frequency of 1.0 Hz along with those from models found in FLAC library. The soil stiffness used in the FLAC model is adjusted to give very similar shear stress-strain responses to those derived from the testing of real soil specimens. Contractive behavior is observed from the results of both the simulations and the physical tests indicating a response that is typical of loose sands.

Figure 8 shows cyclic stress ratio (CSR)-strain responses of two T_xSS conducted on Bais-Saint-Paul sand specimens at a 75 kPa confining pressure and a relative density of 56% at γ_{cyc} values of 0.4% and 0.6% and a frequency of 1.0 Hz along with those obtained from the FLAC model. Figure 9 shows the CSR-γ_{cyc} curves of three T_xSS tests on Olga clay with a plasticity index of

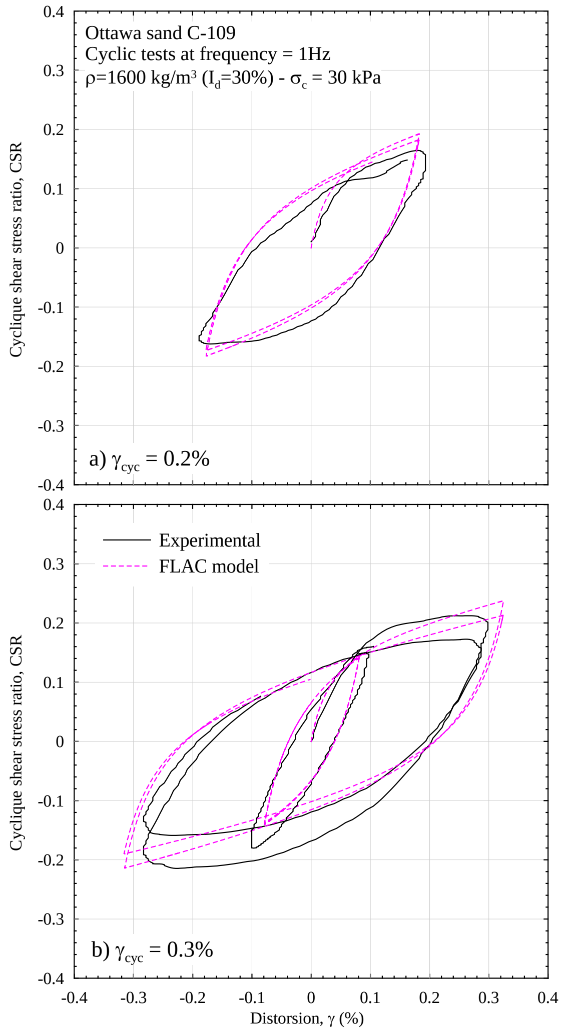


Figure 7. CSR-γ% of the tested Ottawa C-109 sand with those from FLAC.

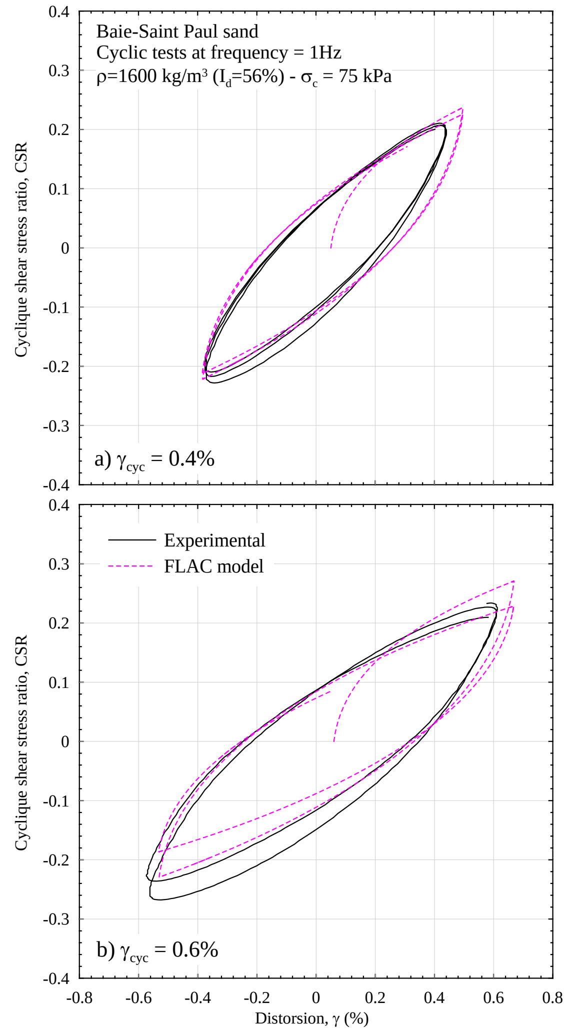


Figure 8. CSR-γ% of the tested Baie-Saint-Paul sand with those from FLAC.

40% and a pre-consolidation pressure, σ'_p of 78 kPa, and tested at a 100 kPa confining pressure performed at γ_{cyc} values of 0.08%, 0.2%,and 0.3% and a frequency of 1.0 Hz along with the corresponding CSR-γ_{cyc} curves from FLAC.

The reliability and (or) performance of the T_xSS is further examined by comparing the results obtained from the T_xSS device as well as those obtained from the FLAC model to geotechnical design charts established in the literature. The test data, when plotted in terms of the ratio of the shear modulus (G) at strain γ to shear modulus at a shear strain of 10^{-4}% (G_{max}) obtained from the calibration using FLAC presented in Figs. 7-9, fall within the relatively narrow band provided by Seed and Idriss (1970) for granular soils as shown in Figs. 10a-11a or that provided by Vucetic et al. (1991) for cohesive soils as shown in Fig. 12a. Figures 10b-12b illustrates also that the experimentally determined damping ratios are in an accepted level of agreement with those obtained from the FLAC simulation and fall in the limits provided by Seed and Idriss (1970) and Vucetic et al. (1991).

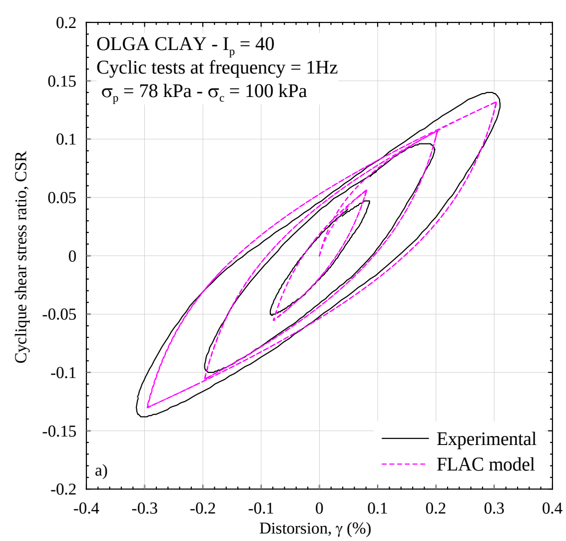


Figure 9. CSR-γ% of the tested Olga clay with a plasticity index of 40% and pre-consolidation pressure, σ'_p of 78 kPa, and tested at a 100 kPa confining pressure with those from FLAC.

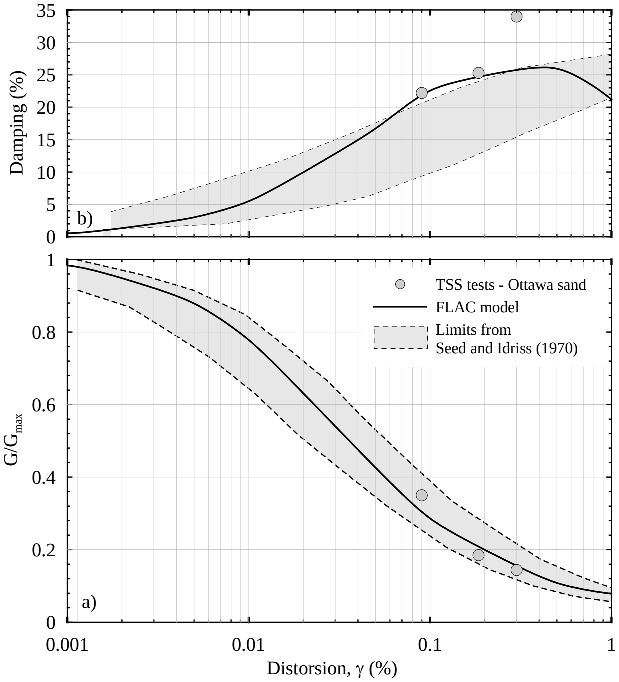


Figure 10. Dynamic characteristic of Ottawa C-109 sand obtained from T_xSS experiments, FLAC model, and design charts provided by Seed and Idriss (1970): (a) G/G_{max}, and (b) damping ratio.

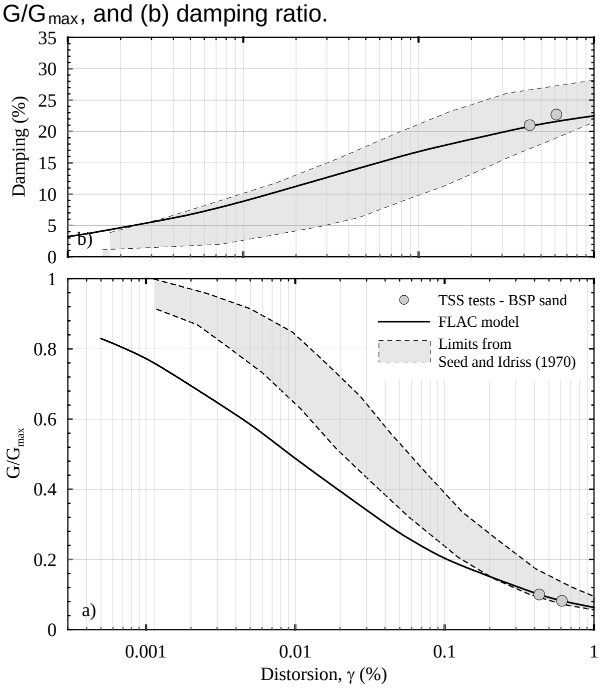


Figure 11. Dynamic characteristic of Bais-Saint-Paul sand obtained from TxSS experiments, FLAC model, and design charts provided by Seed and Idriss (1970): (a) G/G_{max}, and (b) damping ratio.

The comparative results shown in Figs 10-12 indicate that the level of accuracy of the experimental results as well as the FLAC simulations can be regarded as acceptable.

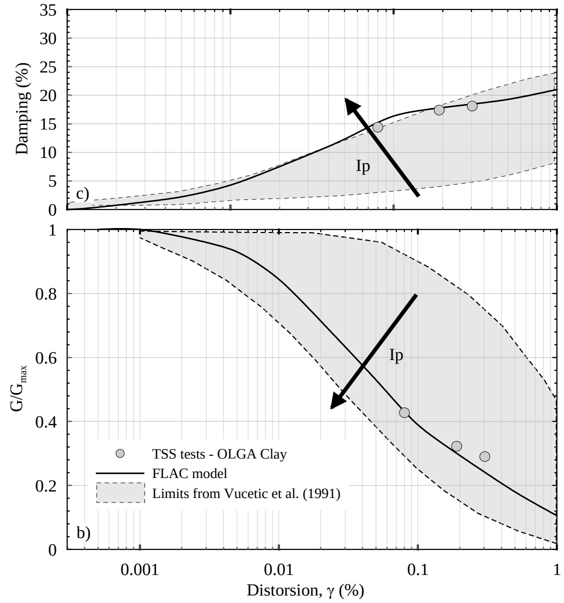


Figure 12. Dynamic characteristic of Olga clay obtained from TxSS experiments, FLAC model, and design charts provided by Seed and Idriss (1970): (a) G/G_{max}, and (b) damping ratio.

The T_xSS apparatus can also be utilized to examine the soil response to real earthquake excitations and this may be of outmost importance in evaluating liquefaction potential of a soil deposit as will be discussed in the following practical example.

The software, FLAC is used to simulate the response of a vertical column of a 20-m Ottawa sand deposit to the 1989 Loma Prieta earthquake shown in the lower plot in Fig. 13. The shear distortion of Ottawa sand located at a depth of 8 m (σ'_c of 75 kPa) computed using FLAC is also presented in Fig. 13. An Ottawa sand specimen is sheared in the T_xSS with the shear strain computed from FLAC at 8 m and the observed time histories of the CSR and r_u are portrayed in Fig. 13. It should be noted from Fig. 13 that although the number of cycles of the irregular time history (Loma Prieta earthquake) shown in the lower plot in Fig. 13 may be sufficient to cause liquefaction of the soil at 8.0 m depth according to the equivalent uniform cycle concept proposed by Seed and Idriss (1975), the maximum observed excess pore pressure, r_u is 0.38 indicating that the tested soil specimen did not liquefied in the T_xSS experiment. This may be attributed to the filtering effects the earthquake wave exposed as it propagates upward.

4 CONCLUSIONS

A wide variety of laboratory apparatuses such as triaxial, direct simple shear, and ring shear devices are now available to evaluate the static and dynamic responses of cohesive and cohesionless soils. However, most of these techniques have their limitations such as the inability to rotate principle stresses; inability to simulate the three-dimensional in situ conditions of soils; the inability to apply confining pressure to the soil samples. Aware of these

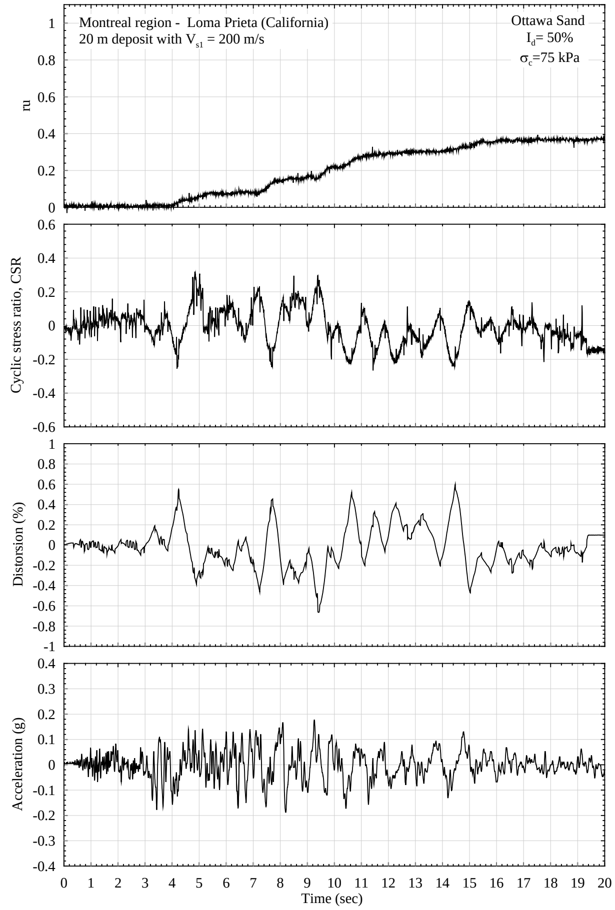


Figure 13. T_XSS test results on Ottawa C-109 sand subjected to the 1989 Loma Prieta earthquake excitation.

limitations, a new combined triaxial simple shear (TxSS) apparatus that minimize their impacts has been design and constructed in the course of a collaboration project between Hydro-Québec and Université de Sherbrooke. The TxSS system consists of a simple shear apparatus incorporated in a triaxial cell for the measurements of static and dynamic characteristics of soil samples.

Comparative TxSS tests on different cohesive and cohesionless soil samples and numerical analyses using the computer code FLAC demonstrate the capabilities of the new apparatus to obtain high quality experimental test data. The obtained experimental data are also compared successfully with established geotechnical design charts found in the literature.

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