

Evaluation of liquefaction resistance of a silty soil using DSS and T_xSS tests

Betegard Jeudy, Mourad Karray

Département de génie civil – Université de Sherbrooke, Sherbrooke, Québec, Canada

Chekired Mohamed

Hydro-Québec, Montréal, Québec, Canada



ABSTRACT

This study presents results of an evaluation of the liquefaction resistance of the Sorel silt using the combined triaxial simple shear apparatus (T_xSS) which allows applying cyclic shear loading as in a direct simple shear test (DSS) on a sample that is saturated, confined and consolidated as in the convention triaxial apparatus. Strain control undrained shear test results, performed with the T_xSS device, are employed to calibrate suitable constitutive soil models. The established models are further employed in numerical simulations considering the energy concept to compute the liquefaction resistance of the tested silty soil using the FLAC software. Stress control and constant volume shear tests with a direct simple shear device (DSS) are also performed to evaluate the cyclic resistance directly. The results show a good agreement between the direct measurements of cyclic resistance (DSS) and the computed values of the cyclic resistance from developed constitutive soil models (T_xSS) for the Sorel silt.

RÉSUMÉ

Cette étude présente les résultats de l'évaluation de la résistance à la liquéfaction du silt de Sorel avec l'appareil de cisaillement simple triaxial qui permet d'appliquer un chargement de cisaillement cyclique comme dans un essai de cisaillement simple direct (DSS) sur un échantillon de sol qui est saturé, confiné et consolidé comme dans l'appareil triaxial conventionnel. Les résultats des essais de cisaillement non drainés en déformations contrôlées, effectués avec l'appareil T_xSS, sont employés pour l'étalonner d'excellents modèles constitutifs de sol. Les modèles établis sont ensuite employés dans des simulations numériques en utilisant le concept d'énergie pour calculer la résistance à la liquéfaction du silt testé à l'aide du logiciel FLAC. Des essais de DSS en contrôle de contraintes sont également effectués pour évaluer directement la résistance cyclique. Les résultats montrent un bon accord entre les mesures directes de la résistance cyclique (DSS) et les valeurs calculées de la résistance cyclique à partir des modèles développés (T_xSS) pour le silt de Sorel.

1 INTRODUCTION

The cyclic triaxial (CTX) and the direct simple shear (DSS) devices have been the most commonly used for the assessment of soils liquefaction during the last decades. The triaxial apparatus assures a real control of the drainage and the confining pressure during the consolidation stage and the shear stage. The soil sample has a cylindrical shape with a height to diameter ratio (H/D) of about 2 and is surrounded by a flexible rubber membrane. The sample is isotopically or anisotropically consolidated and cyclically loaded in the vertical direction through a rigid top cap, and the results are used to assess the cyclic response of the tested soil.

However, the triaxial apparatus faces a significant disadvantage because a cyclic vertical loading does not better represent the replication of an earthquake motion in the laboratory. Therefore, the DSS device may be preferred because it allows applying horizontal cyclic loading, which better represents an earthquake motion (Kwan and El Mohtar 2014; Boulanger et al. 1993). Also, it enables smooth and continuous rotation of the principal stress directions during shearing. This condition appears to more represented the in-situ stress-strain state, unlike the instantaneous rotation of 90 degrees in the triaxial device (Mahmoud et al. 2015). The direct simple shear tests (DSS) can be performed using wire-reinforced

membranes (WR) or stacked rings (SR) to assure K0 conditions and to prevent lateral deformation by maintaining a nearly constant cross-sectional area during consolidation and testing (Donahue 2007). In this equipment, the soil sample is short, with a height of about 15 to 20 mm and a diameter of 80 mm. The constant volume direct simple shear device also has some disadvantage like the inability to saturate the sample, to measure the induced pore pressure and effective stress directly. The pore pressure is measured by operating change in the applied effective stress. Therefore, these drawbacks can limit the use of the DSS test results for the calibration of soil suitable constitutive models (Mahmoud et al. 2015). However, it is shown that the change in vertical stress to maintain the constant volume, allow calculating a pore pressure equal to the measured value with the truly undrained DSS tests. (Dyvik et al. 1987).

As observed, all apparatus have their advantages and their disadvantages. Equipment that can offer more benefits by simulating the in situ loading as closely as possible may be preferable to study the soil's behavior in the laboratory. In that case, a project to combine the advantages of the triaxial and of the DSS in one device has been conducted by the Institut de Recherche d'Hydro-Québec (IREQ) in collaboration with the Geotechnical laboratory at Sherbrooke University. This new device is the combined triaxial simple shear

apparatus (T_xSS) which is a seismic simulator capable of applying the simple shear test on a sample placed in a triaxial chamber (cell). This new apparatus allows the control of the confining pressure and the direct measurement of pore pressure. The tests can be performed in strain control and stress control under monotonic loading and regular and irregular cyclic loading (real earthquake) in drained and undrained conditions. Also, this apparatus allows the acquisition of reliable, high-quality data for calibration models in seismic geotechnical engineering design.

Therefore, the T_xSS apparatus is used in this study to develop data for calibration models and subsequently to compute the liquefaction resistance. The T_xSS tests results are employed for a new approach to assessing the liquefaction or the cyclic softening resistance of soils.

Two specialized laboratory apparatuses were employed: (i) the piezoelectric ring-actuator technique (P-RAT) (Karray and al. 2015) to measure V_s values of soil samples extracted in situ and reconstituted soil sample at different densities to construct V_{s1} - e correlation for each soil type; (ii) the T_xSS seismic simulator to define the cycling shear resistance of soil samples using the V_{s1} measured with the P-RAT as a reference. The dynamic properties obtained from experimental tests were simulated by modeling the cyclic behavior of samples adopting the well-known energy concept following the work of Berrill and Davis (1985) and Green et al. (2000) using the computer code, FLAC (Itasca 2007). For comparison of the results, DSS constant volume tests are also performed to evaluate the liquefaction resistance of the Sorel silt directly.

2 PHYSICAL PROPERTIES OF THE TESTED SOIL SAMPLES

In this study, a plastic silty soil collected from the Sorel region, Québec is used. This soil consists of about 29% clay (fraction < 0.002 mm), 68% silt (0.002 mm < fraction < 0.08 mm) and 3% of fine sandy soils (0.08 mm < fraction < 0.16 mm). With its plastic index of 25, it is identified as clay (CL) by the USCS classification system. However, considering its percentage of silty particles (68%), it is considered as plastic silt.

Table 1 presents the main characteristics of this soil and Fig. 1 shows its particle-size distribution curve.

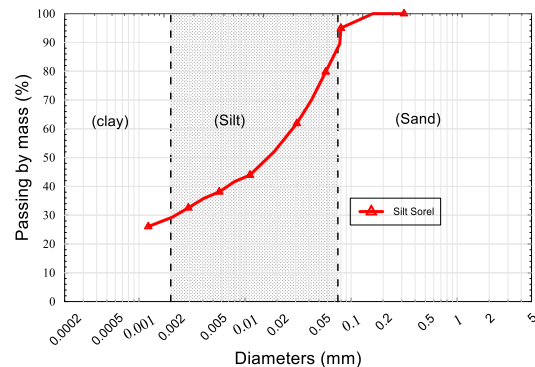


Figure 1. The grain size distribution of Sorel silt.

Table 1: Physical properties of Sorel silt

D_{50} (mm)	C_u	C_c	LL	PL	PI	G_s
0.012	8.0	0.05	31.5	15.5	16	2.79

3 SAMPLES PREPARATION

In the laboratory, soil behavior can be determined from undisturbed and reconstituted specimens. In literature, it is generally recommended that a reconstituted method should be suitable for soil type and its natural deposition process. The technique should facilitate the reproduction of homogeneous samples with similar characteristics (Kurbis and Vaid, 1988).

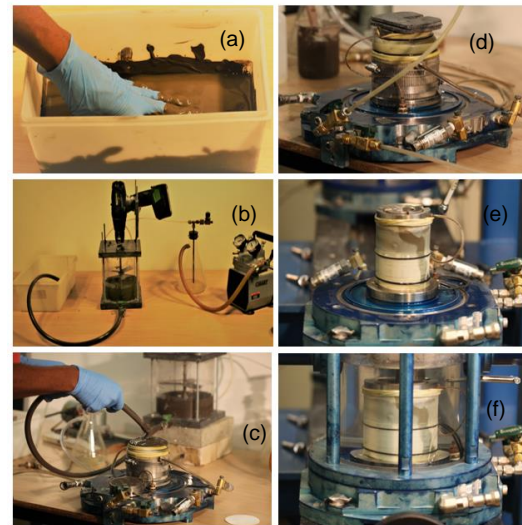


Figure 2. Preparation of T_xSS silt samples.

In this study, the slurry deposition method proposed by Poncelet (2012) is used to reconstituted all the sample because it is a kind of water sedimentation technique adapted for fine-grained soils and in which we attempt to recreate the natural deposition process of the silts. Also, it allows for homogenous soil samples. The preparation steps are shown in Fig. 2. Firstly, it consists of a manual homogenization of the dry soil and the amount of de-aired water required in a tank until we obtain a slurry with a water content well above the liquid limit [Fig. 2(a)]. The mixture is then drawn into an airtight container provided with a rotary shaft which ensures the material mixing. The negative pressure of 40 to 70 kPa is applied for 180 minutes to remove the trapped air bubbles in the mixture [Fig. 2(b)]. The mixture is then transferred to the mold previously filled with water to simulate the deposition in the fluvial environment [Fig. 2(c)]. The sample can be left standing for 90 to 180 minutes before removing the mold depending on the soil. A small load of 1.0 to 2.5 kg and a suction of 4 to 10 kPa can also be applied to accelerate consolidation in the mold [Fig. 2(d)]. After this first consolidation, the water content drops below the liquid limit, and the sample passes into the plastic state. It becomes sufficiently consistent to hold with a flexible membrane without further lateral support. In this

condition, demolding can be done. In this condition, demolding can be done [Fig. 2(e)]. As in a conventional triaxial apparatus, the sample is placed in the cell (T_xSS), which is then filled with water that is pressurized to apply the isotropic confining pressure [Fig. 2(f)]. After saturation, with a Skempton's B value greater than 0.94, the sample is consolidated. After consolidation, the sample which is in triaxial conditions (saturation, drainage, confining, consolidation) is shearing has in a direct simple shear device (DSS) by applying horizontal cyclic loading in undrained condition until the occurrence of initial liquefaction or cyclic failure.

4 LABORATORY TESTING AND RESULTS

4.1. Measurement of shear wave velocity (V_s) using P-RAT

The P-RAT has been developed in the geotechnical laboratory at Sherbrooke University (Karray et al. 2015, Jeudy et al. 2018). The technique can be easily incorporated into conventional geotechnical apparatus such as triaxial and oedometer cells. In this study, it has been incorporated into an oedometer apparatus which allows shear wave velocity measurement during consolidation test. In this study, the P-RAT has been used to determine the shear wave velocity, which can be used subsequently to evaluate the shear stiffness, G_{max} according to the equation [1].

$$G_{max} = \rho V_s^2 \quad [1]$$

The V_s measurements of soils have also been used to construct the relationship between the normalized shear wave velocity (V_{s1}) and the void ratio (e) of the tested soils. The value of V_{s1} can be estimated by equation [2] (Youd et al. 2001).

$$V_{s1} = V_s \left[\frac{P_a}{\sigma'_v} \right]^\beta \quad [2]$$

In this equation, P_a is normal atmospheric pressure in the same units as the effective vertical stress, σ'_v (i.e., $P_a \approx 100$ kPa if σ'_v is in kPa). The exponential β is taken to

0.25 as for a variety of soil ranging from sand to clay (Hardin and Drnevich 1972; Biu 2009).

Typical consolidation curves of the Sorel silt are shown in Fig. 3. Figure 3a presents σ'_v - e curve, and Figure 3b presents σ'_v - V_s curve. Figure 3a shows that the rate of the change in the void ratio with the applied vertical stress is not constant throughout the test. At the beginning of loading (when the soil is slurry), the decrease in the void ratio is more rapid with the applied vertical stress. For instance, between 1 to 120 kPa the void ratio passes from about 1.4 to 0.70 (50% of densification) then from 120 kPa to 300 kPa, the void ratio passes from about 0.70 to 0.62 (11% of densification). This aspect of soil behavior is observed by the increase of the shear wave velocity when the consolidation curve is presented in term of σ'_v - V_s relationship (Fig. 3b).

The P-RAT allows determination of the pre-consolidation pressure because, in the σ'_v - V_s plot, the virgin and the recompression zone are represented by straight lines and their intersection indicate the pre-consolidation pressure (Fig. 3b). We also observe in the recompression zone, the great variation of V_s (σ'_v - V_s plot) in comparison with the variation of the density (σ'_v - e) with the effective vertical stress. This result shows that V_s is influenced by the stress history or by the OCR of the soil. Then the measured shear wave velocities were normalized to the applied effective stress to obtain the normalized shear wave velocity, V_{s1} . To reduce the effect of the stress history, V_{s1} is normalized by OCR at power α which is equal to 0.16 for the Sorel silt. Thus, Fig. 4 shows the variation of V_{s1}/OCR^α with the void ratio, e . As observed in this figure, the value of $V_{s1}/OCR^{0.16}$ is about 150 m/s at a void ratio of 0.55. It means that the values of V_{s1} for this silt are 150 m/s, 167 m/s and 187m/s respectively for the OCR=1, 2 and 4 at the same void ratio of 0.55 (the same density). These results show the soil stiffness and, further, the liquefaction resistance depends considerably on OCR and not only of the density (Dobry and Abdoun 2011, Dobry and Abdoun 2017). Thus, the V_{s1} or the G_{max} is used as a reference to evaluate the liquefaction resistance of the soil.

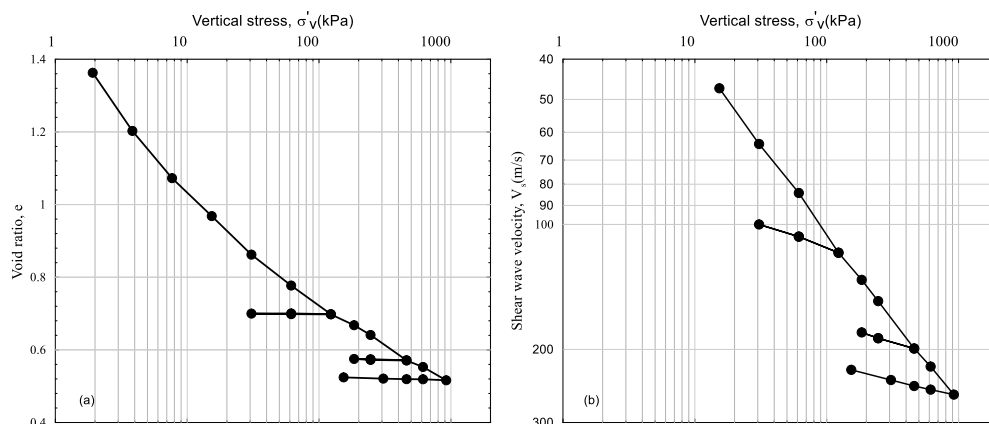


Figure 3. Oedometric curves in terms of a) void ratio and b) shear wave velocity for the Sorel silt.

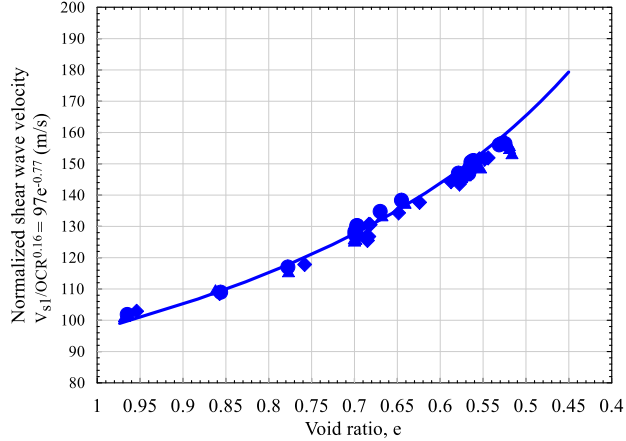


Figure 4. The normalized shear wave velocity as a function of void ratio and OCR for Sorel silt.

4.2. Cyclic TxSS tests to evaluate the cyclic resistance ratio (CRR)

Two ways in this study are used to assess the cyclic resistance of the silty soils. Firstly, strain control tests are performed to developed constitutive soil behavior model with the TxSS apparatus which is a seismic simulator developed by the Institut de Recherche d'Hydro-Québec (IREQ) in collaboration with the Geotechnical laboratory at Sherbrooke University (Chekired et al. 2015). This device allows controlling the direct measurement of the pore pressure and the applying of the confining stresses on a cylindrical soil specimen. The shearing can be performed monotonically or cyclically at different stress amplitudes and frequencies up to 10 Hz. The TxSS device can operate as a DSS by using stacks of annular plates to support the soil specimen laterally. It can also work like the conventional triaxial test if there is no shear loading applied.

The second way to evaluate the cyclic resistance consists of the use of stress control DDS tests with the Dynamic Cyclic Simple Shear device of the GDS Instruments to assess the cyclic strength directly. This device allows to carry out dynamic cyclic shear tests from small frequency (0.01 Hz) to significant frequency (5.0 Hz). In this device, the sample is laterally confined by a reinforced membrane to prevent lateral deformation.

Tables 2 and 3 summarize the conditions of all TxSS and DSS tests. Typical TxSS test results are shown in Figs. 5. The upper left plot [Fig. 5(a)] shows the increase of the measured pore pressure ($R_u = \Delta u/\sigma'_c$) as a function of the time in seconds which results in an exponential decay of the cyclic stress ratio (CSR) defined as the amplitude of the applied cyclic shear stress (τ_{cyc}) divided by the initial effective confining pressure (σ'_c). Figure 5(b) shows the applied shear distortion curve and the increase in vertical axial deformation. Figure 5(c) shows CSR- γ_{cyc} hysteric loops rotate towards the γ axis with the increase in the time or the number of cycles. The area delimited by the loops decreases from cycle to cycle and represents the energy dissipated in the material.

To define soil behavior models, a relation between the cyclic strain, the cyclic stress, and the generated pore pressure are established through the energy concept

(Berrill and Davis, 1985). The normalized unit energy, W_s is defined as the energy dissipated per unit volume of soil divided by the initial effective confining pressure.

Table 2: TxSS tests performed on the Sorel silt.

Test No	γ_c (%)	σ'_c (kPa)	e_c	OCR	B	G_{max} (MPa)
TxS-12-1	2.20	99.0	0.732	1	0.97	31.0
TxS-13-2	1.80	98.3	0.722	1	0.96	31.4
TxS-16-3	1.80	96.0	0.664	1	0.96	36.0
TxS-25-4	0.90	98.0	0.713	2	0.97	59.0
TxS-27-5	1.50	100.0	0.616	2	0.97	52.0
TxS-30-6	0.50	99.0	0.545	4	0.96	80.0
TxS-31-7	1.65	100.0	0.612	4	0.96	66.0

Table 3: DSS tests performed on the Sorel silt.

Test No	CSR	σ'_c (kPa)	e_c	OCR	Nc	G_{max} (MPa)
DSS-1	0.19	100.0	0.630	1	22.0	40.3
DSS-2	0.16	100.0	0.658	1	81.0	37.3
DSS-3	0.23	93.0	0.624	1	8.0	39.4
DSS-4	0.35	97.7	0.649	1	2.0	37.7
DSS-5	0.18	94.0	0.603	1	44.0	42.1
DSS-6	0.52	98.0	0.706	1	0.5	32.6
DSS-7	0.28	100.0	0.622	1	5	41.2
DSS-8	0.38	93.0	0.552	2	19	60.9
DSS-9	0.46	100.0	0.650	2	12	61.6
DSS-10	0.32	98.0	0.561	2	43	60.7

In a cyclic test, the dissipated energy per unit volume can be determined by integrating area bound by stress-strain hysteresis loops as suggested by Green et al. (2000) and as calculated in Eq. 3.

$$W_s^{0.5} = \left[\frac{1}{2\sigma'_{v0}} \sum_{i=1}^{n-1} (\tau_i + \tau_{i+1})(\gamma_i - \gamma_{i+1}) \right]^{0.5} \quad [3]$$

Where $W_s^{0.5}$ is the dissipated energy; τ_i , τ_{i+1} and γ_i , γ_{i+1} are respectively the stress and the cyclic shear strain in the cycle i and $i+1$.

The relationship between the pore pressure ratio, R_u , and the dissipated energy, $W_s^{0.5}$ for the Sorel silt, is presented in the equation [4] and in figure 6 (left plot).

$$Ru = 0.40 \left(\frac{W_s^{0.5}}{a} \right) + 1.60 \left(\frac{W_s^{0.5}}{a} \right)^2 - 1.61 \left(\frac{W_s^{0.5}}{a} \right)^3 + 0.42 \left(\frac{W_s^{0.5}}{a} \right)^4 \quad [4]$$

Where R_u is the pore pressure ratio; $W_s^{0.5}$ is the dissipated energy and (a) is a scalar constant used for grouping ($R_u - W_s^{0.5}$) curves from all tests to define a unique relationship between the pore pressure and dissipated energy for a given soil.

Different factors can influence the amount of generated pore pressure and dissipated energy. For instance, an increase of the density and the OCR can reduce the development of pore pressure and increase the amount of dissipated energy to reach a particular value of pore pressure. Also, the increase of the amplitude of the applied shear strain causes a significant development of the pore pressure and expands the hysteresis loop and consequently increase the dissipated energy. Therefore,

each tested sample can have a proper $(Ru \cdot W_s^{0.5})$ relationship, and to obtain a unique function, the value $W_s^{0.5}$ for each T_xSS test is normalized by a constant (a). The variation of the constant (a) with shear the strain amplitude is shown in Fig. 6(right plot) for OCR=1. The decrease of this constant values reflects the ability of a soil to generate the pore pressure.

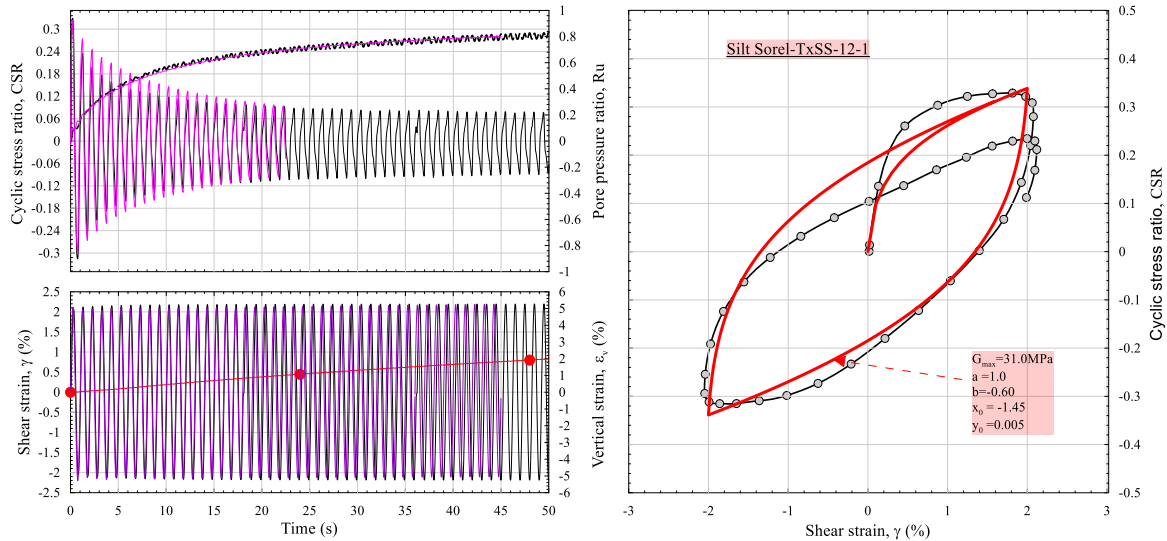


Figure 5. Example of T_xSS test results for the Sorel silt.

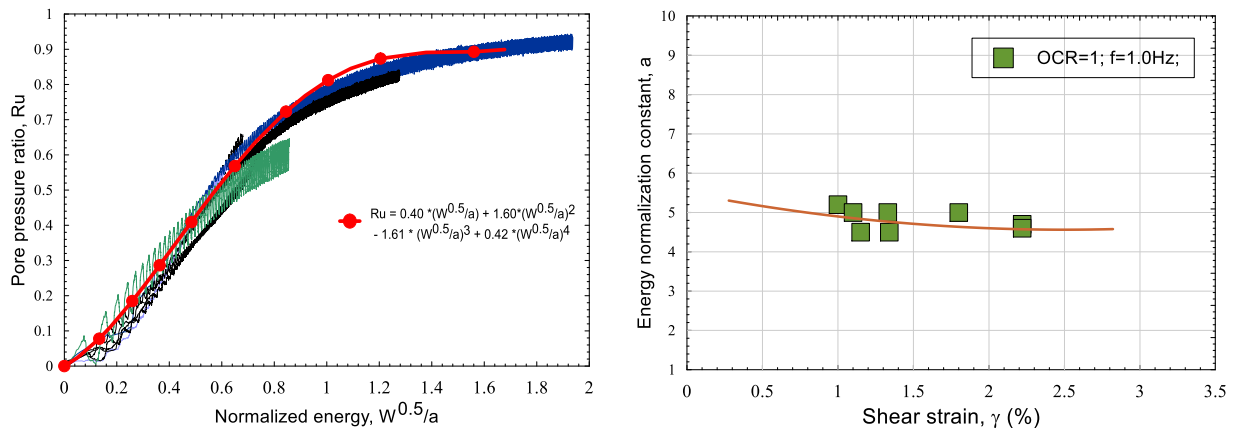


Figure 6. Pore water pressure ratio as a function of the normalized energy (left plot) and Constant (a) as a function of shear strain for the Sorel silt at OCR=1 (right plot).

It is essential to notice that the increase of this constant depends on the OCR, the density, and the frequency. The samples with high OCR values, high density or tested at high loading frequency may show higher constant (a) values. For soils samples tested in the same conditions, the constant (a) values can be close, and the effect of the applied shear strain significantly reduced.

The unique function between the dissipated energy and the pore pressure (equ.4) is used to calibrate the constitutive soil model and to perform an effective stress analysis using FLAC7 (Itasca 2007). The Sig4 function,

as defined in the FLAC software, is used to establish the models that should satisfactorily replicate the cyclic shear response of the experimental test. The parameters of this function are the initial shear modulus (G_{max}) and some constant a_1 , b_1 , x_0 , and y_0 whose values are chosen to calibrate the model on the first loop hysteresis. The sig4 model calibrated (Fig. 7) is presented in terms of degradation shear modulus curve (G/G_{max}) and damping ratio in Fig. 8 for OCR=1. It is to note that these curves of the Sorel silt (IP=16) are located between those proposed by Vucetic for the clayed soils with IP=0 and IP= 15.

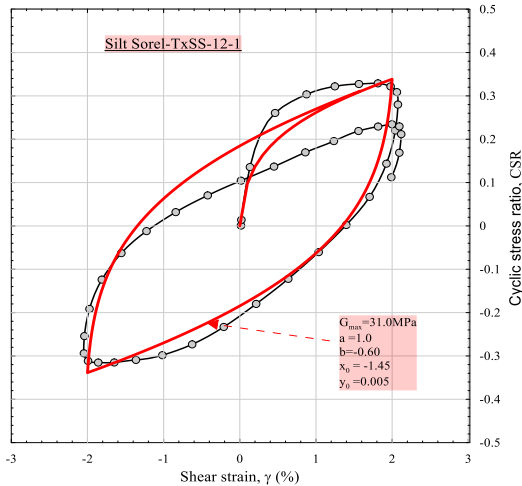


Figure 7. The Sig4 model calibrated on the first hysteresis loop ($f = 1.0$ Hz) of Sorel silt.

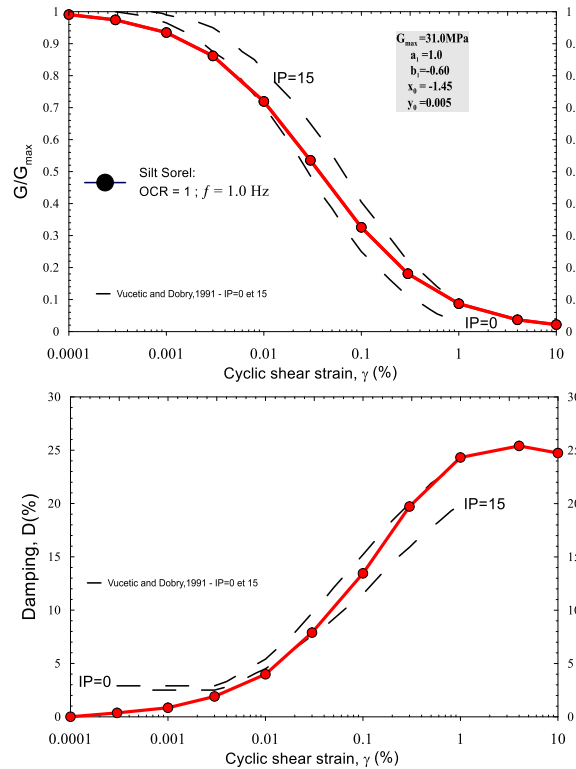


Figure 8. The calibrated Sig4 model in the form of degradation shear modulus curve (G/G_{max}) and the damping ratio curve ($f=1.0$ Hz and $OCR=1$) of the Sorel silt.

Results obtained from the simulation are also plotted with the experimental test results, as shown in Fig. 5. This figure shows good agreement between the pore pressure, the decrease in the cyclic stress ratio, and the hysteresis loops predicted by the simulated model using the energy concept and the experimental T_xSS tests results. After verification of good agreement between experimental results and numerical results, the second series of tests are carried out numerically in stress control to calculate the cyclic resistance ratio required to cause failure by liquefaction or by cyclic softening of the soil.

For the Sorel silty tested, the liquefaction characterized in terms of pore pressure ratio equal to 100% of the effective confining pressure ($R_u=1$) not occurs. For the normally consolidated sample, the pore pressure ratio can reach a value of 0.90 at frequencies less than or equal to unity, but for higher loading frequency and overconsolidated samples, the R_u values can be less than 0.50. In that case, the failure criteria are based on threshold shear strain. Therefore, in this study, the number of cycles required causing cyclic failure (or liquefaction), N_c is defined as the number of cycles to reach to 3% of shear strain in single amplitude as recommended in the literature (Donahue 2007). This value is determined by applying the cyclic stress τ_{cyc} in the numerical modeling of the soil samples in FLAC. Then the Fig. 9 shows the values of the computed cyclic resistance ratio (CRR) versus the number of cycles, N_c ($\gamma=3\%$) at the initial confining pressure of 100 kPa. The continuous line curves represent the computed cyclic resistance for at $OCR=1, 2$ and 4 . The circular dots (green) represent the direct measurements of the cyclic resistance from DSS tests at $OCR=1$. The results show an increase in the cyclic strength with the OCR values.

For the normally consolidated samples ($OCR=1$), the computed CRR curves (Fig. 9) obtained from the T_xSS can be considered as a trend curve that relates different values of resistances (CRR) measured from the DSS. We observe that in the first cycles ($N_c \leq 20$), the CRR in the T_xSS is slightly higher than in the DSS. The tendency with these results seems to reverse with the increase of the number of cycles ($N_c > 40$). However, the results stay close enough. Adding three (3) others results from overconsolidated samples act $OCR=2$, we observe almost the same results between the two apparatus for the same Sorel silt tested. The results show that the combined experimental T_xSS test and numerical simulation of the established soil behavior models and using the energy concept can be used to characterize the soil behavior in regards to liquefaction analysis.

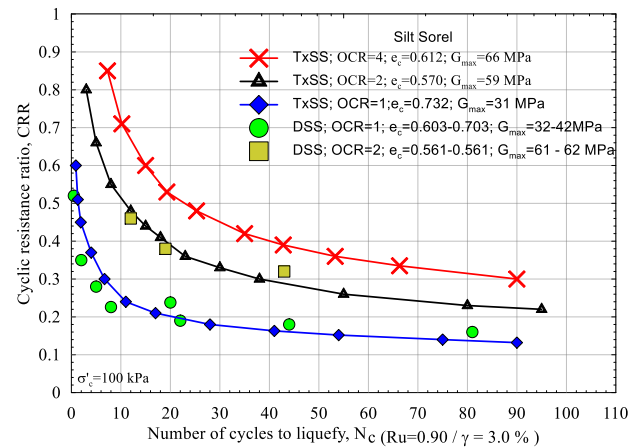


Figure 9. Direct measurement of CRR- N_c and computed CRR- N_c ($\gamma=3\%$) curves of T_xSS tests for an initial confining pressure of 100 kPa and $OCR=1$ for the Sorel Silt.

5 CONCLUSION

In this study, two apparatus had been used to evaluate the liquefaction resistance. Stress control DSS tests to measure directly the cyclic resistance and strain control the TxSS tests to establish constitutive soil models for computing the liquefaction resistance from numerical simulation using the energy concept. Shear wave velocity measurements from the P-RAT apparatus are also performed for the calibration of the models. We observe for normally consolidated samples, consistency results between direct measurement and computed cyclic resistance. These results show that the TxSS can be used for the calibration of suitable constitutive soil models. However, other tests may be performed to continue with comparison and analyze the results for overconsolidated soils samples.

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