Liquefaction assessment from laboratory tests on undisturbed and reconstituted silty soil specimens

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ABSTRACT
Liquefaction charts constructed from in situ tests (e.g. SPT, CPT) and susceptibility criteria are often used for granular and fine-grained soils. With good sampling of clay-like soils, laboratory tests can be used with confidence to assess liquefaction or cyclic softening behavior. For silty and sandy soils, it is difficult to obtain undisturbed samples and also difficult to restore all field conditions (lost by disturbance) with the reconstitution of these materials. However as shear wave velocity, V_s can be measured both in field and in laboratory, and thus it could serve as a reference to reconstitute soil samples. In this paper, a new approach based on experimental and theoretical results is used to assess liquefaction potential (or cyclic softening). Measurements of V_s in laboratory have been utilized to examine the potentiality of using the V_{s1}-e correlation (where V_{s1} is the stress-normalized shear wave velocity) as a reference to reconstitute silt specimens. Then, a series of cyclic combined triaxial simple shear (T_xSS) tests on reconstituted as well as undisturbed silt samples followed by numerical simulation of their dynamic characteristics have been performed to assess their liquefaction potential. The results showed that this new approach using laboratory tests can be used as an alternative to existing methods.

Keywords: Liquefaction, cyclic softening, shear wave velocity, silt, reconstituted samples and undisturbed samples.

RÉSUMÉ
Les chartes de liquéfaction construites à partir des essais in situ (SPT, CPT, Vs) et les critères de susceptibilité sont souvent employées pour les sols granulaires et les sols fins. Avec un bon échantillonnage des sols argileux, les essais de laboratoire peuvent être utilisés en toute confiance pour évaluer le comportement à la liquéfaction ou au ramollissement cyclique. Pour les sols silteux et sableux, il est difficile d'obtenir de spécimens non perturbés et également difficile de rétablir toutes les conditions de terrain (perdues par perturbation) avec les matériaux reconstitués. Cependant, comme la vitesse des ondes de cisaillement, V_s peut être mesurée à la fois sur le terrain et au laboratoire, elle peut servir de référence pour reconstituer les matériaux. Dans cet article, une nouvelle approche basée sur des résultats expérimentaux et théoriques est utilisée pour évaluer le potentiel de liquéfaction (ou ramollissement cyclique). Des mesures de vitesse en laboratoire sur des spécimens intacts et reconstitués sont utilisées pour examiner la possibilité d'employer la corrélation V_{s1}-e pour reconstituer les spécimens. Ensuite, une série de tests de cisaillement triaxial combiné cyclique (T_xSS) sur des spécimens intacts et reconstitués, suivi par des simulations numériques de leurs caractéristiques dynamiques ont été effectués pour évaluer leur potentiel de liquéfaction. Les résultats montrent que cette nouvelle approche utilisant les essais de laboratoire peut être utilisée comme une alternative aux méthodes existantes.

1 INTRODUCTION

Damages during an earthquake are in the most cases induced by natural phenomena such as tsunami, landslides and soil liquefaction. Liquefaction is particularly associated with the behavior of loose sandy soils. However, recent earthquakes revealed that fine-grained soils such as silts and clays can also undergo significant loss of rigidity and large deformation called cyclic softening which is relatively different from the cyclic mobility or liquefaction of sands (Boulanger and Idriss 2006).

The liquefaction potential in current practice is firstly evaluated with liquefaction charts constructed from in situ measurements (e.g., standard penetration test blow count, N-SPT; cone penetration resistance, q_c-CPT and shear wave velocity, V_s) and historical seismic data (Robertson and Wride, 1998; Youd and al., 2001). This approach was developed for granular soils containing less than 35% fines. For fines grained soils, the liquefaction's susceptibility criteria were based mainly on field observations during historic earthquakes (Seed and Idriss, 1982). However, these criteria are very limited and did not account for some important factors that have real effects on the soil response such as stress history, amplitude and duration of cyclic loading (Sunitsakul, 2004). Moreover, the use of these criteria would cause significant errors in soil classification with respect to liquefaction and it will be possible to classify a soil as non-liquefiable while it had been liquefied in reality and vice versa (Boulanger et al. 1998).

Recently, Boulanger and Idriss (2007) proposed a new procedure to evaluate the potential of cyclic softening in fines-grained soils similar to the approach developed for granular soils. In this approach, the cyclic resistance ratio (CRR) can be evaluated directly from cyclic shear tests or by empirical correlations with undrained shear strength (τ_u) and the over consolidation ratio (OCR). The direct measurement of the soil resistance provides the highest level of confidence, and so it is better to use laboratory test to evaluate the CRR (Donahue, 2007; Sanin 2010).

This study presents a new approach that can be used to assess the liquefaction of sandy soils or the cyclic softening of fines-grained soils. The procedure comprises the combined use of both practice and theory to define the cycling shear resistance and cyclic behavior 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 validated by modelling 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).

2 PHYSICAL PROPERTIES OF THE TESTED SOIL SAMPLES

The silty soil studied was extracted between 3.8 and 4.0 m depth from the Laurentides station site in Charlesbourg borough, Québec. This deposit consists mainly of a very dense till with presence of alluvium in the north of the station. In this area, the *H/V* method has been used. This method generally uses the ratio between the Fourier amplitude spectra of the horizontal (H) and the vertical (V) components of the ambient noise vibrations to define the predominant frequency of a certain soil deposit. This method shows a deposit's natural frequency, f_0 =4.27 Hz. To better replicate the natural vibration in case of earthquake, the frequency of 4.0 Hz comparable to frequency of the deposit is used to test undisturbed and reconstituted samples extracted from this site. The undisturbed soil has a coefficient of uniformity, Cu=49 and a curvature coefficient Cc=1.8. The soil is classified as sandy silt (30 % of sand) with graded particle size distribution. Its plastic index is 9.8% and its liquidity limit is 24.6%. According to the USCS classification system, the soil is classified as CL. The reconstituted soil is the same material in which the sandy particles greater than 0.16 mm are removed (Fig. 1). The physical properties of the tested soils samples are listed in Table 1, while its grain-size distribution curve is shown in Fig. 1.

Table 1: Physical properties of Laurentides soil (TM2)

D_{50} (mm)	C_u	C_c	W_p	W_L	G_s
0.032	49	1.8	14.8	24.6	2.763
0.012	25	0.6	-	-	-

3 SAMPLES PREPARATION

In the laboratory, soil behavior can be studied from undisturbed and reconstituted specimens. Test on undisturbed samples help to understand the actual soil characteristics in the field. However, for some soils, it is difficult to extract, transport and maintain undisturbed samples. These difficulties increase from clay to low-plastic silt and become almost impossible in clean sands. To study the behaviour of such soils, a reconstituted technique may be necessary. Therefore, tests are performed on undisturbed sandy silt samples and on reconstituted silt samples prepared with fraction smaller than 0.16 mm of the sandy silt (Fig.1).

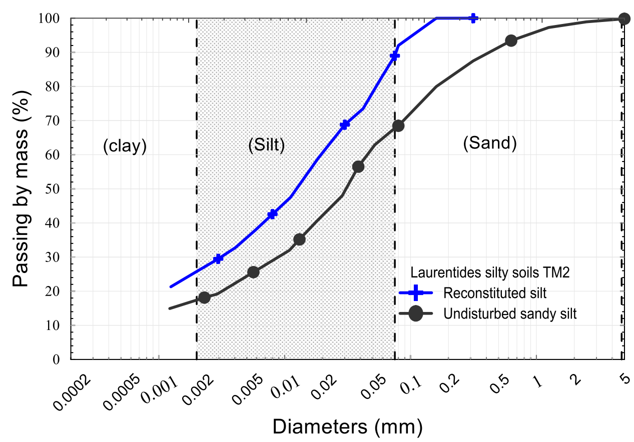

Figure 1. Grain size distribution of Laurentides silty soils.

It is recommended that a deposition method should be suitable to soil type and its natural deposition process. It should facilitate the reproduction of fairly homogeneous samples with similar characteristics (Kerbis and Vaid, 1988). In this study, the slurry deposition method proposed by Poncelet (2012) is used 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 silts. In addition, it allows 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 liquidity limit [Fig. 2(a)]. The mixture is then drawn into a hermetic container provided with a rotary shaft which ensures the material mixing. A 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 material. A small load of 2 to 4.5 kg and a suction of 4 to 10 kPa can be also applied to accelerate consolidation in the mold [Fig. 2(d)]. Once the sample wrapped by a membrane becomes self-sustaining, demolding is done [Fig. 2(e)]. Finally, it is placed in the cell which is then filled with water for cell and sample pressures application according to the general procedure of triaxial test [Fig. 2(f)]. After saturation, with a Skempton's B value greater than 0.94, the sample is isotopically consolidated. After consolidation, a cyclic loading under undrained condition is applied to the sample until the occurrence of initial liquefaction or cyclic rupture.

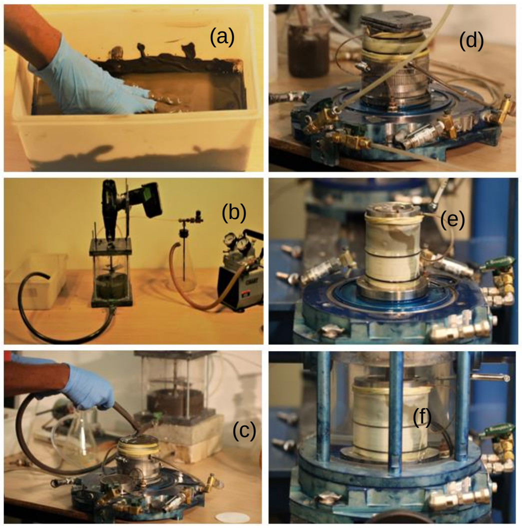

Figure 2. Preparation of T_xSS silt samples.

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). 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. The P-RAT essentially consists of two parts: an emitter and a receiver (Fig. 3). Each part is a piezoelectric inert ring. The transceiver system is connected to a computer via an acquisition and a wave generator card. The system comprises a signal generator connected to the piezoelectric transmitter ring. Between the generation of the signal and the transmitter, an amplifier of the signal power is used. The process consists of emitting a wave through the power amplifier to the piezoelectric transmitter ring which vibrates in the radial direction. A porous stone is fitted inside the ring using a special epoxy to allow the propagation of shear wave when the coupled ring-stone system is in contact with the soil specimen. The wave reaches the receiver ring that connected to an oscilloscope where its velocity is measured after signal processing. The P-RAT has been used to determine the shear wave velocity of soils and 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 the equation [1] (Youd et al. 2001).

$$V_{s1} = V_s \left[\frac{P_a}{\sigma_v^{'}} \right]^{\beta} \quad [1]$$

In this equation, P_a is normal atmospheric pressure in the same units as the effective vertical stress, σ'_v (i.e., $Pa \approx 100$ kPa if σ'_v is in kPa). The exponential β is taken to 0.25 for a variety of soil ranging from sand to clay (Hardin and Drnevich 1972; Biu 2009).

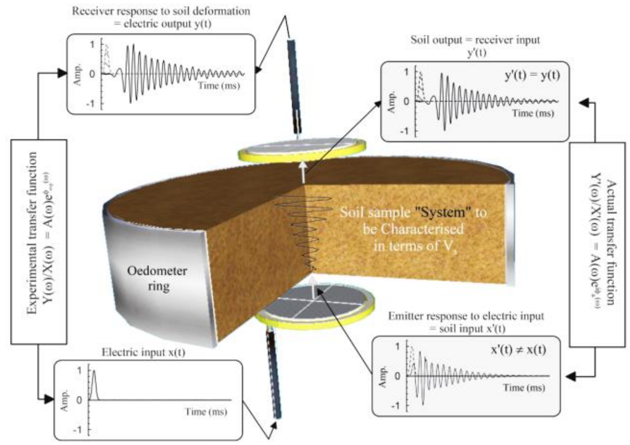

Figure 3. Schematic of experimental P-RAT test (Karray et al 2015).

Typical consolidation curves are shown in Fig. 4 for both samples. Figure 4(a) presents σ'_v-*e* curves that show the change in the void ratio with the applied vertical stress, while Fig. 4(b) presents σ'_v-V_s curves that show the change in the shear wave velocity with the applied vertical stress. For the undisturbed sample, the preconsolidation pressure is about 320 kPa and it indicates an over consolidation ratio of about 6 (σ'_v is about 55 kPa at the in situ sampling depth). The P-RAT test allows determination of the pre-consolidation pressure because in the σ'_v-Vs plot, virgin and recompression zone are represented by straight lines and their intersection can unequivocally be found indicating the pre-consolidation pressure (Fig. 4b). In contrast, if a soil sample has undergone significant disturbance, it would be difficult to distinguish between recompression and virgin zones. Also the ratio $\Delta e/e_0$ is used in literature to evaluate the quality of sample with respect to the disturbance (Krage et al. 2015; Lunne et al. 2006). Where e_0 is the initial void ratio and Δe is the difference between e_0 and the void ratio corresponding to the in situ effective vertical stress (55 kPa). In this study, the ratio $\Delta e/e_0$ is less than 0.04, it means that the sample is good and it can be considered as undisturbed. For reconstituted sample, several cycles of loading and unloading were performed to simulate the effect of pre-consolidation pressure. it can be observed in Fig. 4(a) a rapid decrease of the void ratio due to the applied vertical stress. Thus, the applied pressure causes less variation in the soil structure (due to consolidation) of the undisturbed sample.

The measured shear wave velocities were normalized with respect to the applied effective stress to obtain the normalized shear wave velocity, V_{s1}. In order to reduce the effect of over consolidation, V_{s1} is normalized by OCR at power α which is equal to 0.07 and 0.14 respectively for reconstituted and undisturbed samples.

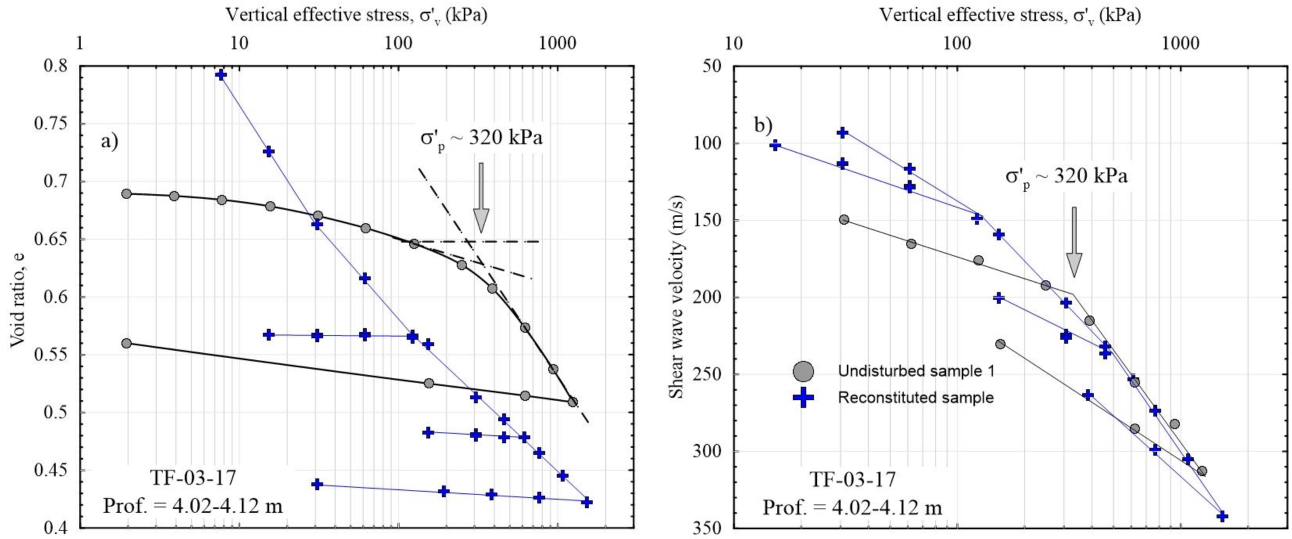

Figure 4. Oedometric curves in terms of: a) void ratio and b) shear wave velocity for undisturbed and reconstituted samples.

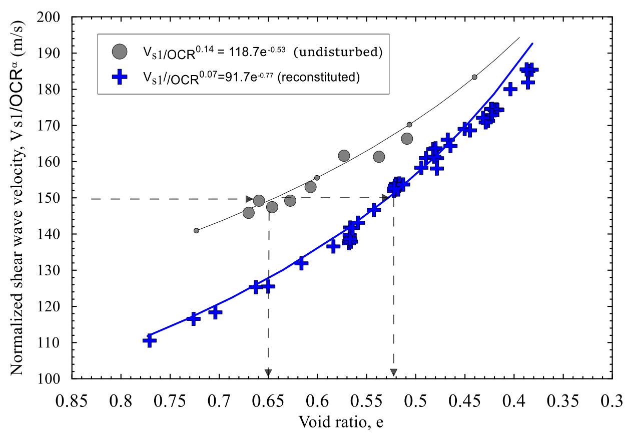

Figure 5. Variation of the normalized shear wave velocity as a function of void ratio and OCR.

Thus, Fig. 5 shows the variation of $V_{s1}/\mathrm{OCR}^{\alpha}$ with void ratio, e. As expected, despite having a looser density the undisturbed sample shows higher values of normalized shear wave velocity. For example, the undisturbed sample has a $V_{s1}/\mathrm{OCR}^{\alpha}$ of 150 m/s at void ratio of 0.65 while reconstituted sample shows the same velocity at a void ratio of 0.52. The result may not only due to the soil fabric effect, but also to the particles size distribution as shear wave velocity is directly proportional to the D_{50} and inversely proportional to the percentage of fines (Karray et al. 2011; Choo and Burns 2015).

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

The cyclic resistance of soil is evaluated using the T_xSS 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 apparatus is designed to apply simple shear test on sample in triaxial-test conditions. The device allows a complete control of the cyclic shear strain which is the main factor to control the increase in the pore pressure and thus liquefaction. A series of strain-controlled undrained T_xSS tests were performed at both undisturbed and reconstituted samples. Tables 2 and 3 summarize the conditions of all T_xSS tests. Typical T_xSS test results are shown in Figs. 6 and 7 respectively for undisturbed and reconstituted samples. In both figures, the upper left plot [Fig. 6(a) and Fig. 7(a)] shows the increase of the 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 ($\tau_{cyc.}$) divided by the initial effective confining stress (σ'_c). It is possible to notice that the decrease in the CSR in the reconstituted sample is greater than that in the undisturbed sample. This result indicates that the undisturbed sample has a more stable and resistant structure. However, greater CSR of the undisturbed sample can be due to the same factors that increase the shear wave velocity (soil fabric effect and particles size distribution) but also due to the confining pressure which is 59 kPa for the undisturbed sample and 102 kPa for the reconstituted sample because soils are more resistant to liquefaction at low effective confining stress (Hoque et al. 2017). Figure 6(b) shows the applied shear distortion curve and the increase in vertical axial deformation of the sample. Figure 6(c) shows CSR-γ_{cyc} hysteric loops rotate towards the γ axis with the increase in the time or in the number of cycles. The area delimited by the loops decreases from cycle to cycle and represents the energy dissipated in the material.

As the T_xSS tests are performed in strain-control conditions, a relationship must be established between the cyclic stress and the cyclic strain ratios in order to use the strain-control test results in the existing liquefaction charts that are established using the cyclic stress ratio, CSR. With the new approach, a relation between the cyclic strain, the cyclic stress, and the generated pore pressure is 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. 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. 2.

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

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

The first loop can also be used in the estimation of the initial shear modulus (G_{max}). In addition, G_{max} and G/G_{max} can be evaluated with the T_xSS from very low to high shear strains. However in this study the G_{max} is evaluated from Vs measurement in P-RAT test according to its relationship to shear wave velocity and unit weight of the soil:

$$G_{\max} = \rho V_s^2 \quad [3]$$

Figures 8(a) and (c) show the relationship between the pore pressure ratio, R_u, and the dissipated energy, $W_s^{0.5}$ for each soil sample. To obtain this function, the value $W_s^{0.5}$ for each T_xSS test is normalized by a constant (a). The variation of constant (a) with shear strain amplitude is shown in Figs. 8(b) and 8(d). It is important to notice that this constant depends on OCR, density and shear strain amplitude. Its decrease reflects the ability of material to generate pore pressure. The samples with high degree of over consolidation or with a high density may show greater values of the constant (a) as presented in Fig. 8(d). For example, when the applied shear strain is about 1.0%, the constant values are about 6, 7, 9 and 11 respectively for reconstituted samples at OCR=1 (e_c≈0.66), OCR=2 (e_c≈0.59), OCR=4 (e_c≈0.54) and OCR=4 (e_c≈0.51). Where e_c is the index void ratio after consolidation.

Table 1: T_xSS tests performed on undisturbed samples of Laurentides TM2 silt.

Test No	γ_{cyc} (%)	σ'$_c$ (kPa)	e_i	e_c	OCR	B	N_{liq} (Ru=0.70)
T_xSS-1i	0.60	53.0	0.697	0.665	6	0.92	120
T_xSS-2i	0.70	58.0	0.716	0.689	6	0.94	-
T_xSS-3i	0.85	58.0	0.704	0.700	6	0.94	320
T_xSS-4i	1.04	59.0	0.722	0.708	6	0.95	300
T_xSS-5i	1.45	55.0	0.743	0.717	6	0.92	120

Table 2: T_xSS tests performed on reconstituted samples of Laurentides TM2 modified silt.

Test No	γ_c (%)	σ'$_c$ (kPa)	e_i	e_c	OCR	B	N_{liq} (Ru=0.70)
T_xSS-1	1.1	98	0.776	0.660	1	0.98	140
T_xSS-2	0.65	98	0.77	0.636	1	0.95	400
T_xSS-5	0.21	104	0.728	0.657	1	0.98	800
T_xSS-6	0.92	104	0.710	0.591	2	0.95	300
T_xSS-7	0.65	102	0.706	0.580	2	0.95	420
T_xSS-8	0.50	106	0.728	0.595	2	0.95	500
T_xSS-9	0.35	103	0.686	0.586	2	0.94	750
T_xSS-10	0.95	105	0.696	0.535	4	0.98	300
T_xSS-11	0.45	101	0.672	0.549	4	0.95	500
T_xSS-12	0.95	103	0.747	0.540	4	0.97	200
T_xSS-13	1.20	102	0.682	0.514	4	0.95	250
T_xSS-14	1.25	106	0.579	0.515	4	0.95	170
T_xSS-15	0.65	106	0.679	0.512	4	0.94	450

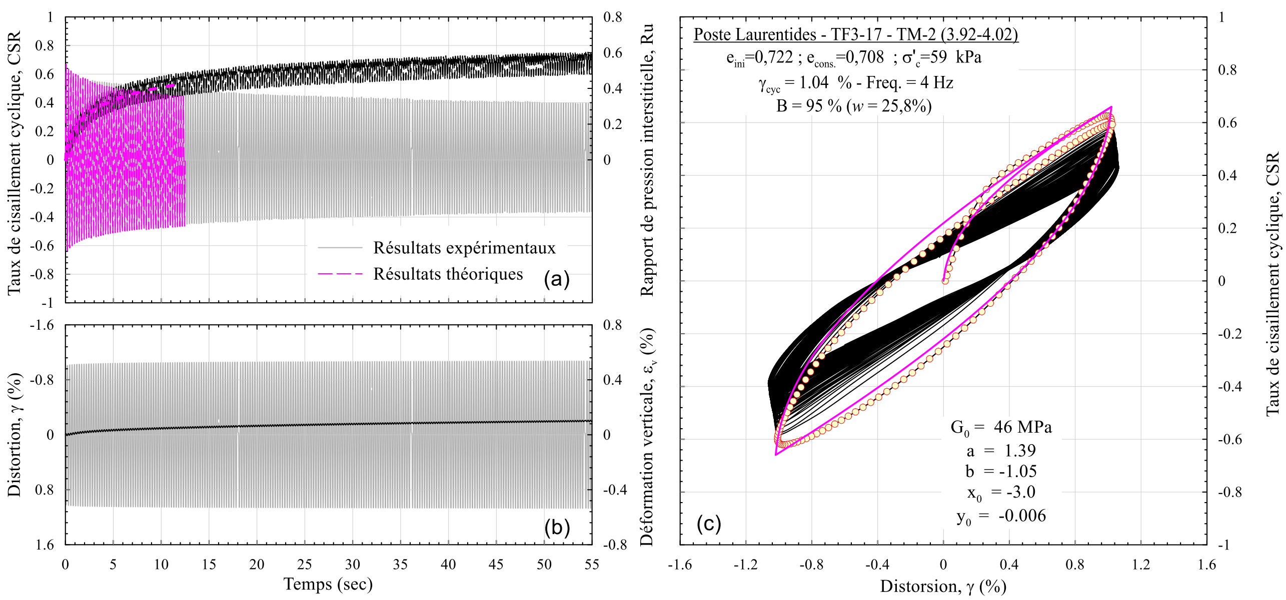

Figure 6. Example of T_xSS test results for undisturbed sample.

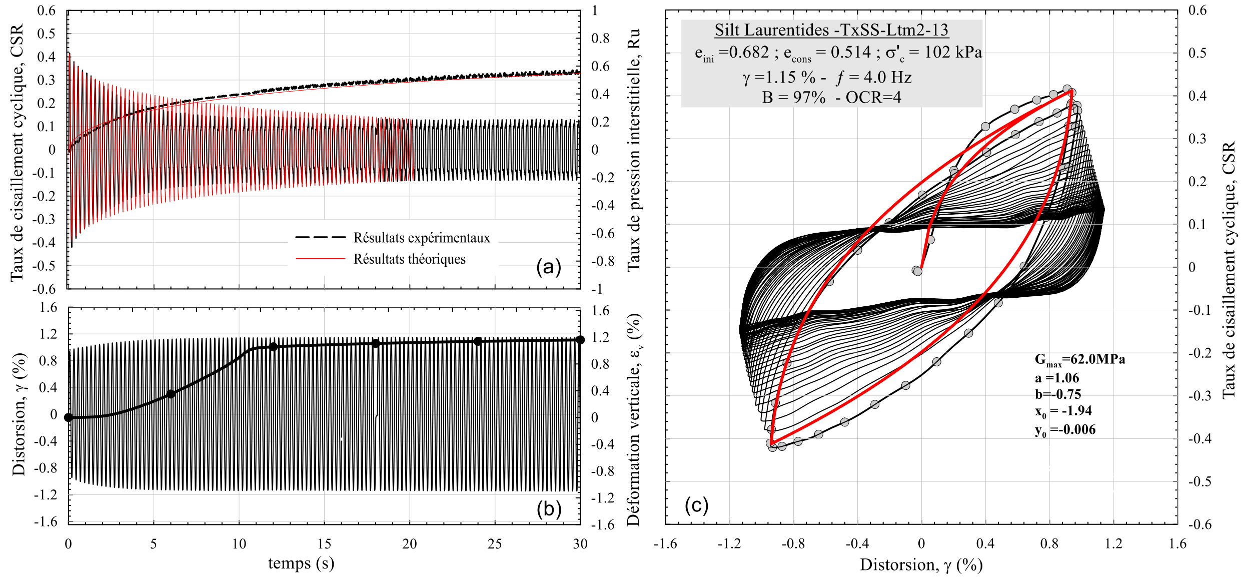

Figure 7. Example of TxSS test results for reconstituted sample

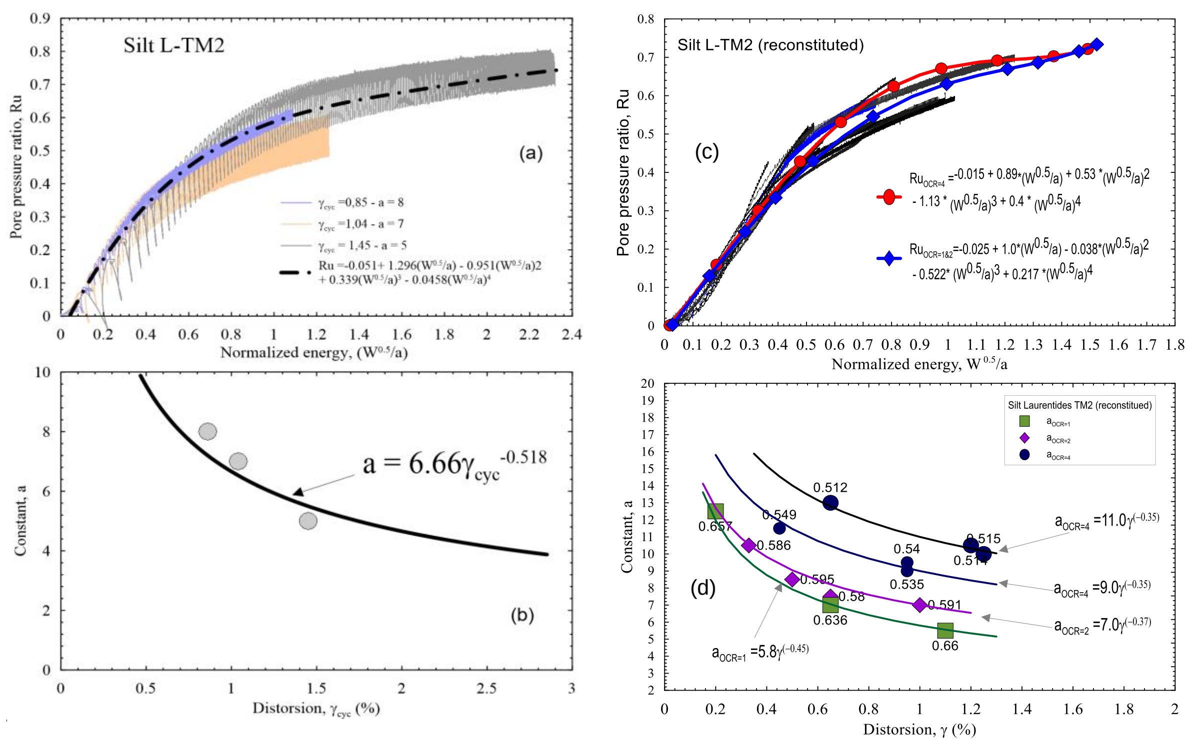

Figure 8. Pore water pressure ratio as a function of the normalized energy and Constant (a) as a function of shear strain for undisturbed samples (a, c) and for reconstituted samples (b, d).

In order to determinate the cyclic resistance ratio (CRR) that can be used in the evaluation of liquefaction potential or cyclic softening, the initial shear modulus (G_{max}) and the first hysteresis loop are used to calibrate a numerical model behavior that should satisfactorily replicate the cyclic shear response of the experimental test. The unique function between the dissipated energy and the pore pressure is used with the numerical model behavior to perform an effective stress analysis using FLAC7 (Itasca 2007). This approach makes it is possible to take into account the increase of the pore pressure resulting from the degradation of the material on the cyclic resistance. This is an advantage over most existing methods (Dobry and Abdoun 2017).

Results obtained from the simulation are plotted in Figs 6 and 7 respectively for undisturbed and reconstituted samples. These figures show good agreement between numerical and experimental results for both types of samples. In this study, the number of cycles required causing cyclic failure (or liquefaction), N_c is defined as the number of cycles to reach an excess pore water pressure ratio, R_u of 0.7. This value is determined by applying the cyclic stress τ_{cyc} in the numerical modelling of the soil samples in FLAC. Figure 9 shows the values of the computed cyclic resistance ratio (CRR) versus the number of cycles, N_c (R_u=0.7 for undisturbed and reconstituted samples at different OCRs and at the same initial confining pressure of 100 kPa.

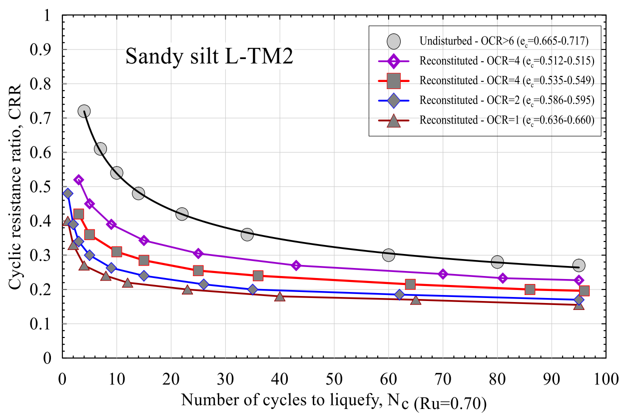

Figure 9. Computed CRR-Nc (Ru = 0.7) curves of T_xSS tests for an initial confining pressure of 100 kPa.

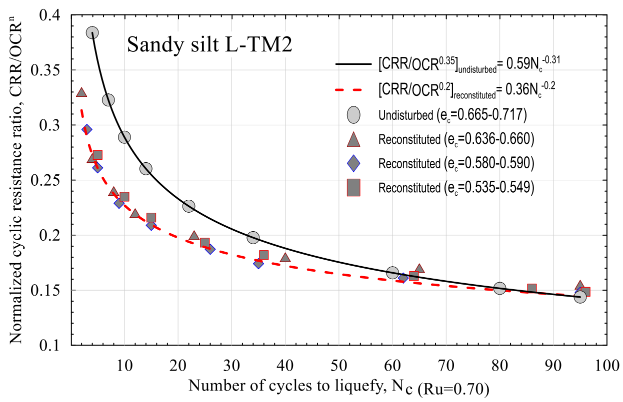

Figure 10. CRR/OCR^n against Nc (Ru = 0.7).

The findings indicate that computed cyclic resistance ratio (CRR) increases with the increase in the soil's OCR. The effect of the OCR has already established by previous studies (e.g., Donahue 2007; Sanin 2010). All the computed values of cyclic resistance ratio (CRR) are normalized by their OCRs and the ratio CRR/OCR^n is plotted versus Nc (Ru=0.7) in Fig. 10, where the exponent n is selected at 0.20 for the reconstituted samples to make the best fit of all the points. As the undisturbed samples show a structure more resistant at the same OCR, the exponent n is selected at 0.35 for undisturbed samples to make a comparable fitting with the reconstituted samples. As observed in the figures, undisturbed sample shows higher ratio CRR/OCR^n due to difference in the soil fabric and the aging effect between undisturbed and reconstituted samples.

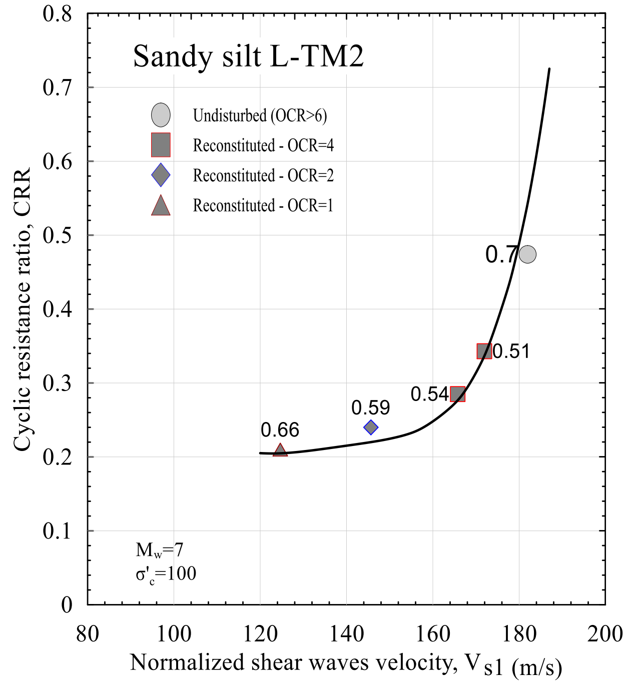

Figure 11. Computed CRR-Vs1 curves of T_xSS tests on Laurentides TM2 silt for an earthquake magnitude, Mw of 7.5 and for an initial confining pressure of 100 kPa.

In Fig. 11, the computed cyclic resistance ratio (CRR) obtained for reconstituted samples at different OCR (1, 2, and 4) and at OCR=6 for undisturbed sample for an earthquake magnitude, M of 7.5, and an initial confining pressure of 100 kPa is plotted against the normalized shear wave velocity, V_{s1}. Figure 11 indicates that the computed cyclic resistance ratio increases with increase in the soil's OCR and its normalized shear velocity or with the decrease in the void ratio whose values are shown at each point in the figure.

It is also observed that even the undisturbed sample has higher void ratio, it shows higher cyclic resistance (Fig. 11) and higher shear wave velocity (Fig. 5). Trying to reconstitute samples at the same void ratio or the same OCR may not be enough to reach the in situ resistance because the aging and the soil fabric effect play a significant role. In addition if the particles size distribution differs, the result can be also different. Reconstitution of the material at the same V_{s1}, the same confining pressure, the same OCR may give some closer result to the field behavior. These results are consistent with previous studies comparing the results obtained with undisturbed and reconstituted samples (Wijewickreme and Sanin 2008; Hoeg et al. 2000). Thus, this approach can be well used as an alternative to existing methods for the evaluation of the cyclic response of soils. However, further study may follow this work for better assessment of liquefaction or cyclic softening resistance of soils in situ.

5 CONCLUSION

In this study, a new method combined laboratory test and numerical simulation to perform an effective stress analysis of liquefaction (or cyclic softening) by using the relation between the generated pore pressure and the energy dissipated during the degradation dynamic behavior of soil samples. The laboratory tests included measurement of shear wave velocity through P-RAT system and cyclic resistance by the T_xSS apparatus on undisturbed sandy silt and reconstituted silt samples. As observed, undisturbed samples show a soil structure more resistant, more stable and with higher shear wave velocities compared to the reconstituted samples even if the void, e and the over consolidation, OCR ratios are the same or the void ratio is higher for undisturbed samples. Numerical simulation had also shown a higher liquefaction resistance (CRR) for undisturbed samples.

Following this tendency, reconstituted samples at the same void ratio and the same OCR may give lower cyclic resistance compare to undisturbed samples due to the aging and soil fabric and particles size distribution. These results, however, are consistent with previous studies comparing the results obtained with undisturbed and reconstituted samples. However, further study may follow this work for better assessment of liquefaction or cyclic softening resistance of soils in situ.

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