Evaluation of compatibility between existing liquefaction charts in Eastern regions of North America

Mourad Karray & Mahmoud N. Hussien
Department of Civil Engineering, Faculty of Engineering, Sherbrooke University, Sherbrooke, QC, Canada
Mohamed Chekired
Hydro-Québec, Montréal, Québec, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
A comprehensive set of seismic (regular and irregular) loading tests on granular soil samples have been conducted using the new combined triaxial simple shear (T_xSS) apparatus in order to examine the applicability/performance of the available liquefaction chart used in Eastern Canada. The T_xSS system consists of a simple shear apparatus incorporated in a triaxial cell for the measurements of dynamic characteristics of soil samples. With T_xSS, it is possible to conduct simple shear tests under control confining pressure, drained or undrained conditions, and using arbitrary seismic loadings. In this study, different granular soil samples are subjected to seismic loading obtained from response analyses using the computer code, FLAC on soil deposits subjected to earthquakes compatible and incompatible with the Eastern seismicity. The experimental and the computed results are compared, and the comparison confirmed the accuracy and the reliability of the T_xSS test results as well as the adopted numerical model, and demonstrated that liquefaction charts used in the Eastern regions of North America, based on experience from other regions in the world, should be revisited.

RÉSUMÉ
Un ensemble d'essais de chargement sismiques (réguliers et irréguliers) sur des échantillons de sol granulaires ont été menés en utilisant l'appareil de cisaillement simple triaxial (TxSS) afin d'examiner l'applicabilité / performance des chartes de liquéfaction avec la séismicité de l'Est du Canada. Le système TxSS est composé d'un appareil de cisaillement simple incorporé dans une cellule triaxiale pour les mesures des caractéristiques dynamiques des du sol. Avec TxSS, il est possible de procéder à des essais de cisaillement simple sous des pressions de confinement contrôlées, en conditions drainées ou non drainées, et en utilisant des charges sismiques arbitraires. Dans cette étude, différents échantillons de sols granulaires ont été soumis à des chargements sismiques obtenues à partir de l'analyse de la réponse dynamique, utilisant le code informatique FLAC, d'un dépôt soumis à des tremblements de terre compatibles et incompatibles avec la sismicité de l'Est. Le résultats expérimentaux et calculés sont comparés et la comparaison confirme la fiabilité des résultats de lapareil TxSS. L'étude montre que les chartes de liquéfaction utilisées dans les régions de l'Est de l'Amérique du Nord, basée sur des expérience d'autre région du monde, devrait être revu.

1 INTRODUCTION

Soil liquefaction is a crucial issue in the design of foundations to sustain dynamic loading. Since 2005, the National Building Code of Canada (NBC 2005) imposes a systematic analysis of the liquefaction potential of a soil stratum. These demands have a direct impact on civil engineering projects with respect to the cost related to the treatment of the soil and the selection of the foundation type. In fact, the liquefaction problem is accommodated in the regions of the world with high seismicity (e.g., United States (Western regions), Japan, and China), but remains poorly documented for the Eastern regions of North America, because of the lack of historical events. In practice, the evaluation of liquefaction potential is generally based on the charts established from observations made after earthquakes in the United States, Japan and China, and, using the soil parameters derived from sounding (e.g., N: standard penetration test (SPT) or q_c: cone penetration test (CPT)) as well as V_s measurement. Although, different in geological and geotechnical characteristics in general and seismicity context in particular, similar charts of liquefaction potential evaluation are applied to the running geotechnical applications in Eastern regions of North America. In fact, there is an increasing need for a more precise evaluation of the applicability and performance of the seismic chart, in general use today in the Eastern regions of North America.

For this reason, a series of seismic (regular and irregular) loading tests on granular soil samples have been conducted using the new combined triaxial simple shear (T_xSS) apparatus (Chekired et al. 2015). The T_xSS system consists of a simple shear apparatus incorporated in a triaxial cell for the measurements of dynamic characteristics of soil samples. With T_xSS, it is possible to conduct simple shear tests under control confining pressure, undrained conditions, and using arbitrary seismic loadings. In this study, granular soil samples from Baie-Saint Paul and well documented Ottawa sands C-109 are subjected to seismic loading obtained from response analyses using the computer code, FLAC on soil deposits subjected to earthquakes compatible and incompatible with the Eastern seismicity. The cyclic soil behavior in FLAC is modelled adopting the well-known energy concept following the work of Berrill and Davis (1985) and Green et al. (2000) after experimental calibration. The experimental and the computed results are compared. Details of the experimental setup, tested material, FLAC simulation, and practical implication are given in the following sections. Primary findings from this study are summarized as conclusions.

2 THE USED T_XSS APPARATUS AND THE TESTED MATERIAL

Cyclic triaxial simple shear test (T_xSS) apparatus (Chekired et al. 2015), used in this study, was designed to provide confining pressure to the soil specimen during simple shearing by a regular or irregular wave forms. Baie-Saint-Paul samples obtained from the Couvant Baie-Saint-Paul (Québec, Canada) site and an calibrated Ottawa sand C-109 were used in this study with their properties summarized in Table 1. The grain-size distribution curves of the two sands are shown in Fig. 1. Wet tamped preparation method was used to prepare reconstituted soil specimens in a rubber membrane. The soil specimen was 76 mm in diameter and 25.8 mm height. Moist sand was placed in three layers and every layer compacted to the desired density. After saturation, with a Skempton's B value greater than 0.97, the sample was isotropically consolidated to an initial stress ratio of $k_o = (\sigma'_h/\sigma'_v) = 1$, where σ'_v and σ'_h are the effective vertical and horizontal stresses, respectively. After consolidation, the specimens were subjected to cyclic shear strain under undrained condition until initial liquefaction occurred. Initial liquefaction is defined throughout this study as the excess pore pressure, $r_u = u/\sigma'_{co}$, of 0.9 as shown in Figs. 2b, where u is the residual pore pressure; σ'_{co} is the initial effective confining pressure.

3 TYPICAL RESULTS OF CYCLIC T_XSS TESTS

A series of undrained cyclic strain-controlled tests on Ottawa C-109 and Baie-Saint-Paul sands under isotropic stress conditions and at different values of γ_{cyc} is conducted until initial liquefaction occurred.

Table 1: Physical properties of the used sands

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

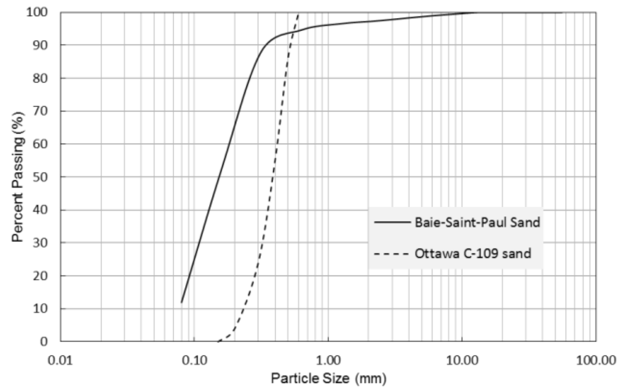

Figure 1. Grain size distribution curves of the used sands

The sample preparation method and the testing procedure mentioned above were almost the same in all tests. All tests have been carried out at the initial effective confining pressure of 30 and 75 kPa for Ottawa C-109 and Baie-Saint-Paul sands, respectively, and at the same loading frequency of 1 Hz. Typical response of the Baie-Saint-Paul sand response to cyclic loading are presented in Figs. 2a-c. In particular, Fig. 2a shows that the reduction in shear stiffness of the soil due to the act of cyclic shear strain is associated with an increase in the vertical deformation of soil structure ε_v. Figure 2b monitors the excess pore pressure built up with the progress of loading. Figure 2b indicates that the soil is totally liquefied (r_u = 0.9) after 25 cycles. Figure 2b shows also that the increase of the excess pore pressure, r_u, with strain cycles results in exponential decay of cyclic stress ratio (CSR). Where, CSR is defined as the amplitude of the applied cyclic shear stress ($\tau_{cyc.}$) divided by the initial effective confining stress (σ'_{co}). Figure 2c shows the variation of cyclic stress ratio CSR with the applied cyclic shear strain, γ_{cyc}. It is important to note from Figs. 2c, that the CSR- γ_{cyc} hysteric loops rotates toward the γ axis with the increase in the number of cycles, and the bounded area representing the dissipated energy decreases with further cycles.

4 VALIDATION OF THE ENERGY-BASED CONCEPT USING THE T_XSS TEST RESULTS

The T_xSS test results are utilized to examine the performance of the well-known energy-based concept for evaluating liquefaction potential and residual excess pore pressure generation first introduced in the 1970s as an alternative to stress-based procedures developed by prof. Seed and his colleagues at University of California at Berkeley (e.g., Nemat-Nasser and Shokooh 1979). Energy-based pore pressure models typically relate the ratio of excess pore pressure (r_u) generated during shearing to normalized unit energy, W_s that can be defined as the energy dissipated per unit volume of soil divided by the initial effective confining pressure (Polito et al. 2013). Where the dissipated energy per unit volume for a soil sample in cyclic loading can be determined by integrating area bound by stress–strain hysteresis loops as suggested by Green et al. (2000) and schematically

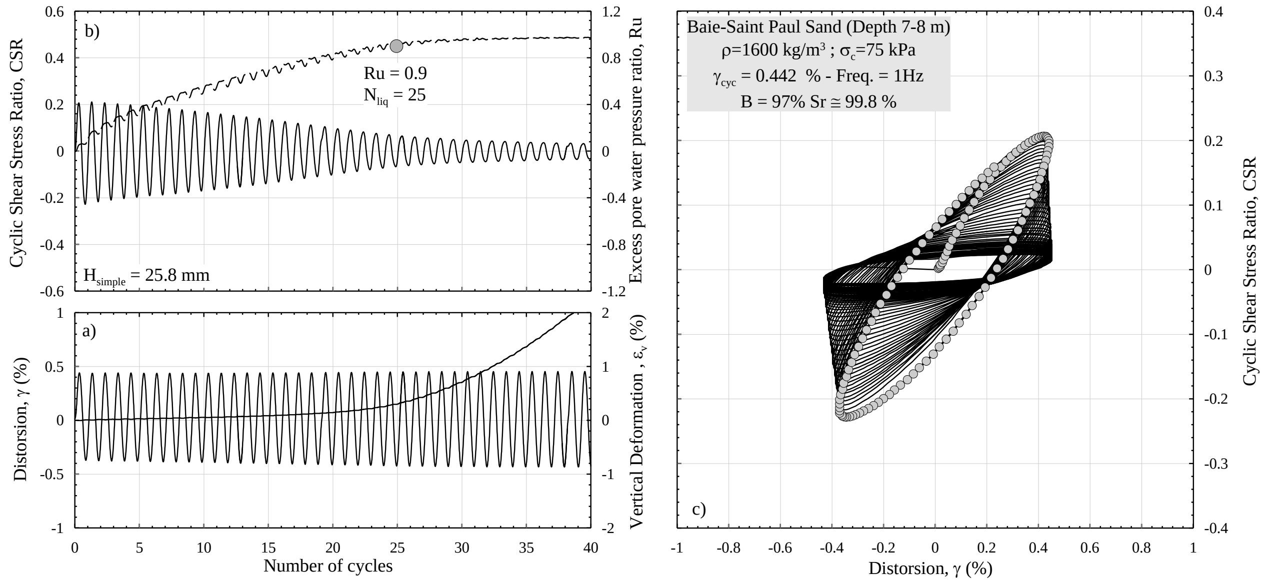

Figure 2. Typical records of T_xSS test on Baie-Saint-Paul sand

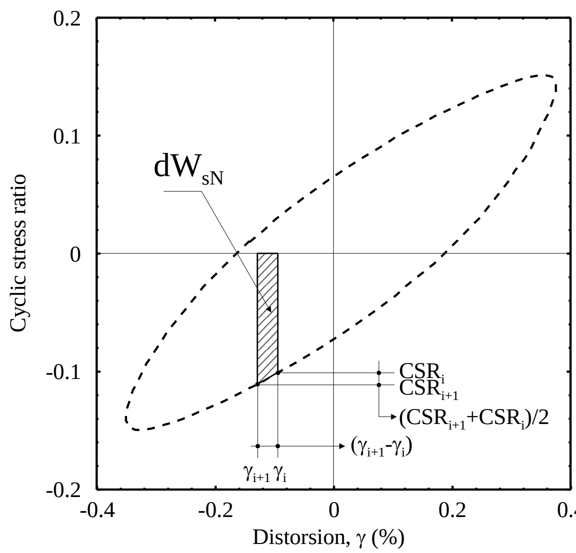

Figure 3. Dissipated energy per unit volume for a soil sample in cyclic T_xSS test determined by integrating area bound by stress-strain hysteresis loops

plotted in Fig. 3. Berrill and Davis (1985) proposed an early empirical energy-based model to relate r_u to W_s:

$$r_u = \alpha W_s^{\beta} \quad [1]$$

where α and β are calibration parameters. Equation 1 can be written as:

$$r_u = \alpha_1 \left(\frac{W_s^{0.5}}{a}\right)^{\beta_1} \quad [2]$$

where α_1, β_1, and a are calibration parameters that can be determined for each soil type from experimental data.

The energy dissipated per unit volume of soil divided by the initial effective confining pressure for different T_xSS tests on samples of Bais-Saint-Paul and Ottawa sands tested under different applied shear strains are plotted against the generated excess pore pressure in Figs. 4a and 4b, respectively. The r_u-W_s curves shown in Figs. 4a and 4b are adjusted so that all curves in the same figure fall in a narrow range by adjusting the calibration parameter a. Figure 5a and 5b show the variations of the calibration parameter of Bais-Saint-Paul and Ottawa sands with the applied shear strain (Fig. 5a) and with the number of cycles to liquefaction (Fig. 5b). Figure 5 illustrates that the calibration parameter, a, is a function of the strain level and greatly change from material to other. The parameter a can be correlated to the strain level for Bais-Saint-Paul and Ottawa sands, respectively as:

$$a_{Baie} = 0.87\gamma_{max}^{-0.8} \quad \text{for Baie-Saint-Paul sand} \quad [3]$$

$$a_{Ottawa} = 0.354\gamma_{max}^{-0.455} \quad \text{for Ottawa sand} \quad [4]$$

Based on the experimental results presented in Fig. 4a and 4b, the general correlation between r_u and W_s given in Eq. 2 can be rewritten, respectively for Bais-Saint-Paul and Ottawa sands as:

$$r_u = \left(\frac{W_s^{0.5}}{a_{Baie}}\right)^{1.327} \quad [5]$$

$$r_u = 1.112\left(\frac{W_s^{0.5}}{a_{Ottawa}}\right)^{1.74} \quad [6]$$

The performance of the energy-based procedure represented in Eqs. 5 and 6 is examined against experimental data from the T_xSS tests on Bais-Saint-Paul and Ottawa sands using different irregular loading as shown in Fig. 6-8. In particular, Figure 6-8 show a comparison between the computed excess pore pressure ratios computed using Eqs. 5 and 6 with those measured in the experiments on Bais-Saint-Paul (Figs. 6 and 7) and Ottawa (Fig. 8) sand specimens. It is important to note

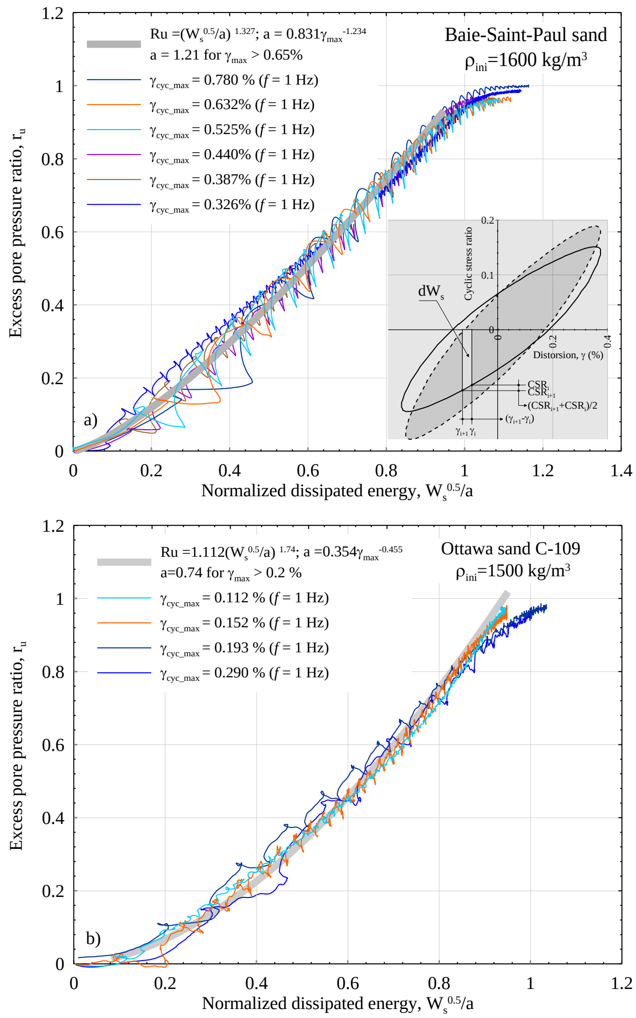

Figure 4. r_u-W_s for soil samples tested in the cyclic T_xSS: (a) Baie-Saint-Paul sand; (b) Ottawa sand C-109

that different sequence of loading is used in Fig. 6 and Fig. 7. On the other hand, Fig. 8 (for Ottawa sand) shows the buildup of pore pressure due to applied shear strain that increases with the number of cycles. Figures 6b-6b indicate that there is an excellent agreement between the measured and the computed excess pore pressure regardless of the tested sand, the type and sequence of the applied loading.

The computer code, FLAC (Itasca 2010) is employed to simulate the T_xSS tests on Bais-Saint-Paul sand. In the analysis, the pore pressure development during shearing is modeled in FLAC using the energy concept referred to the above correlations between r_u and W_s given in Eqs. 5. The computed total stress cyclic response of Baie-Saint-Paul sand samples extracted from a depth of 7-8 m adopting the experimentally-determined r_u-W_s correlation (Eq. 5) is compared to that measured in the T_xSS as shown in Figs. 8a-b. The left and right hand sides of Fig. 8 represent, respectively the comparison at applied shear strain γ_{cyc} of 0.445% and 0.63%. The increase in the excess pore pressure, r_u, with strain cycles (Fig. 9a) results in a gradual decrease in the cyclic stress ratio (CSR) (Fig. 9b).

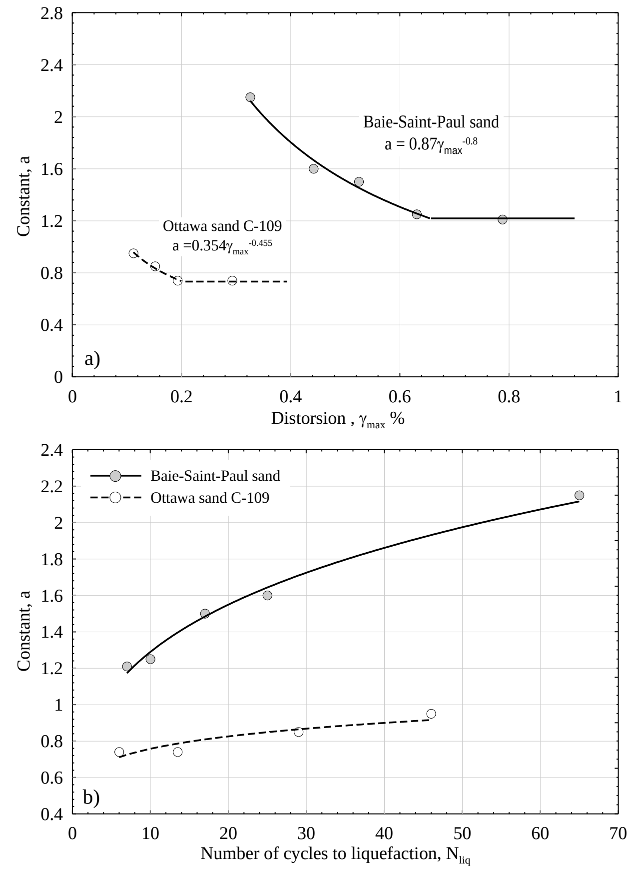

Figure 5. Calibration parameter versus: (a) distortion; (b) number of cycles to liquefaction

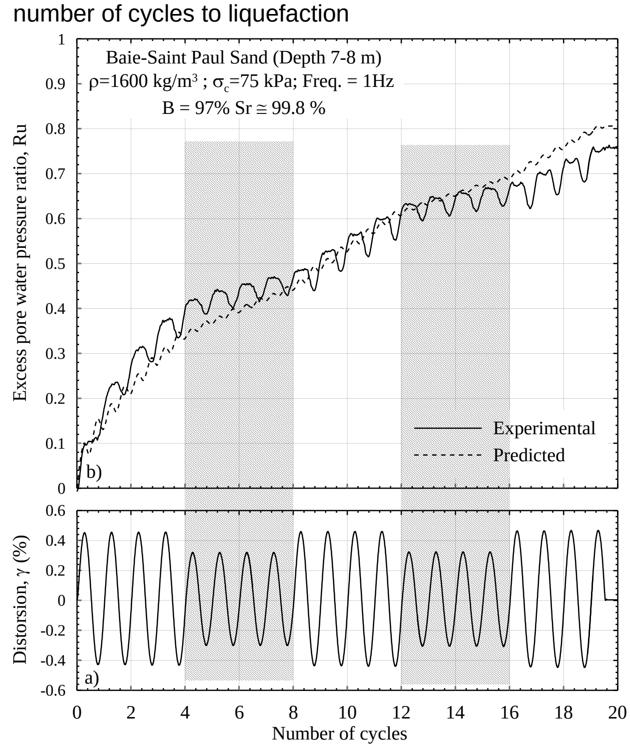

Fig. 6. Comparison of measured versus predicted excess pore pressure ratios for irregular loading 1: Baie-Saint Paul sand.

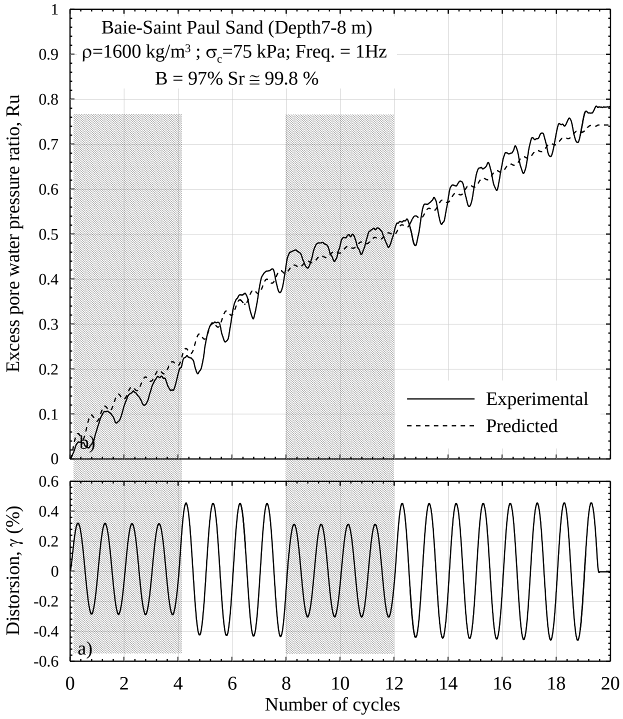

Fig. 7. Comparison of measured versus predicted excess pore pressure ratios for irregular loading 2: Baie-Saint Paul sand

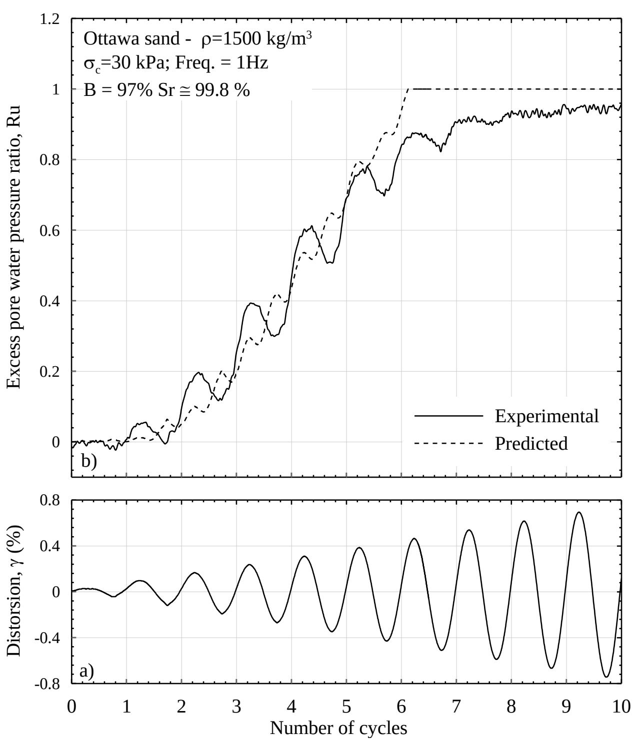

Fig. 8. Comparison of measured versus predicted excess pore pressure ratios: Ottawa sand

It is evident from Figs. 9a and 9b that the predictions of the FLAC model are in satisfactory agreement with the experimental results. The comparison can be considered as good for all practical design purposes. Consequently, the used FLAC model that adopt the dissipated energy theory to model the buildup of the excess pore pressure has a reasonable applicability to capture the essential behavior of the cyclic response of Baie-Saint Paul sand samples tested in the T_xSS.

It is worth noting that the computed cyclic stress ratio (CSR) when normalized by the quantity $((1-r_u)^{0.5})$ shows a constant value during shearing for both shear strain values used in the analysis presented in Fig. 9c. This proves/confirms the ability of the adopted numerical model to account for (simulate) the rotation of the CSR-γ_{cyc} hysteric loops toward the γ-axis as well as the reduction in the dissipated energy (i.e., the bounded area) with further shearing (i.e., the increase in the number of cycles). Figure 10 presents the measured CSR- γ_{cyc} hysteric loops (right plot) compared to the computed loop (left plot). This figure illustrates the effectiveness of the adopted model to simulate the cyclic sand behavior observed in the physical tests at different applied shear strain γ_{cyc} of 0.445% and 0.63%. These results imply that although the adopted FLAC model is based on the total stress theory, it can predict satisfactory the effective stress soil characteristics measured in the laboratory experiments.

5 EVALUATION OF COMPATIBILITY BETWEEN EXISTING LIQUEFACTION CHARTS IN EASTERN REGIONS OF NORTH AMERIC

The computer code, FLAC is used to analysis the seismic response of the Baie-Saint-Paul deposit located at Baie-Saint-Paul site (Québec) and extended to a depth of 250 m. More details about the site and the in situ measurements conducted can be found in (Karray et al. 2011). Two types of earthquake records are used in the analysis; the first one (Atkinson 2009) is compatible with the 2005 NBCC; while the second one is a real earthquake is not compatible with the 2005 NBCC. The NBCC 2005 spectrum for Baie-Saint-Paul site on NBCC (class A) is compared to the used compatible (Atkinson 2009) and incompatible records in Fig. 11.

Figures 12 and 13 show comparison between the measured and the computed responses of Baie-Saint-Paul sand under the action of the compatible and incompatible records, respectively. In Figs. 12 and 13 the computed shear strains at a depth of 7-8 m (σ'_c of 75 kPa) from the ground surface using FLAC due to both the compatible and incompatible records are applied to the Baie-Saint-Paul sand sample tested in the T_xSS apparatus under the same confining pressure (σ'_c of 75 kPa) and the measured time histories of the excess pore pressure (r_u) as well as the cyclic stress ratio (CSR) are compared to the computed time histories as depicted also in the top plots in Figs. 12 and 13. The results in Figs. 12 and 13 exhibit some features that warrant explanations:

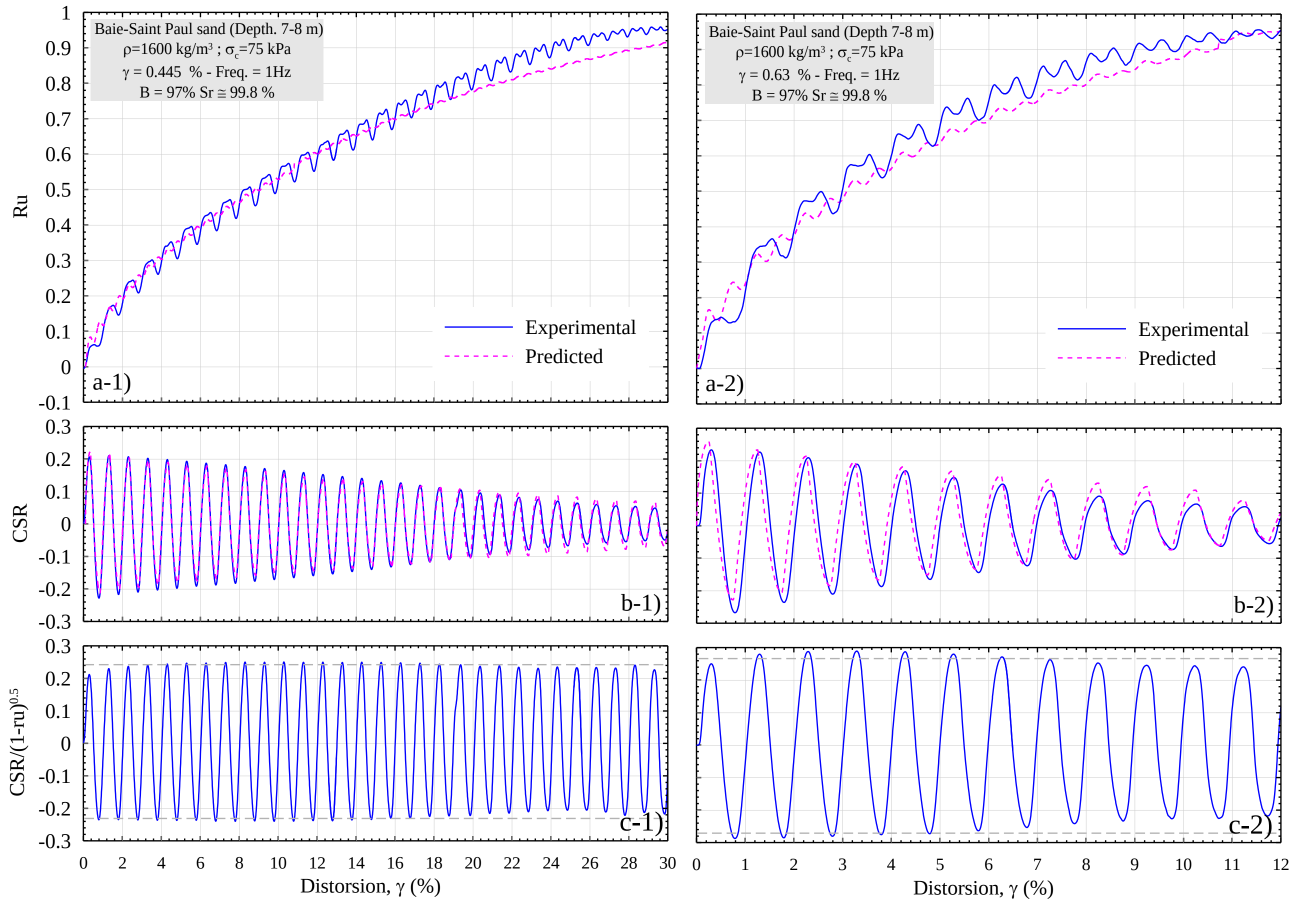

Fig. 9. Comparison of measured versus predicted Baie-Saint-Paul sand cyclic response tested at γ_{cyc} of 0.445% and 0.63%: (a) excess pore pressure; (b) CSR; and (c) CSR/(1-r_u)$^{0.5}$

1. The measured and the computed responses in terms of r_u and CSR are very similar. This similarity confirms the accuracy and reliability of the T_xSS test results as well as the energy-based model adopted in FLAC.
2. The used records have very different acceleration amplitudes. The maximum excitation amplitude is respectively about 1.0g and 0.18g for the compatible and incompatible records. The former record (compatible) is very rich with high frequency components compared to the latter one.
3. The shear distortions presented show filtering effects the earthquake wave exposed as it propagates upward.
4. Although the measured and computed CSRs (≈ 0.21) are the same in both Figures (Fig. 12 and Fig. 13), the soil is totally liquefied due to the action of the incompatible record (Fig. 13) after 16 sec, but not liquefied due to the compatible record (Fig. 12). The maximum attainable r_u in Fig. 12 is about 0.4. These results, in fact, have two folds impact in the undertaken efforts for evaluation liquefaction potential at least in the Eastern regions of North America. First they question the use of the stress-based procedures first introduced by prof. Seed and his colleagues adopting the CSR or the equivalent uniform cycle concept proposed by Seed et al. (1975). Second, they Raise doubts on the compatible records in current use in the Eastern America to evaluate liquefaction potential. Figures 11 and 12 illustrate clearly that the current charts for liquefaction potential should be revisited.

6 SUMMARY AND CONCLUSIONS

In order to examine the applicability/performance of the current seismic chart used in Eastern regions of North America, a set of cyclic tests on Baie-Saint Paul and Ottawa sand samples have been conducted using the 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 dynamic characteristics of soil samples. The experimental data is then used to calibrate the energy-based concept following the work of Berrill and Davis (1985) and Green et al. (2000) for pore pressure generation modeling. As a part of this study, ground response analyses on Baie-Saint Paul site in Québec are done using the computer code, FLAC adopting the experimentally-calibrated energy-based data using earthquake records compatible and incompatible with the Eastern seismicity. The computed shear strains (at 7-8 m) due to both records are applied to samples from the same soil in the T_xSS.

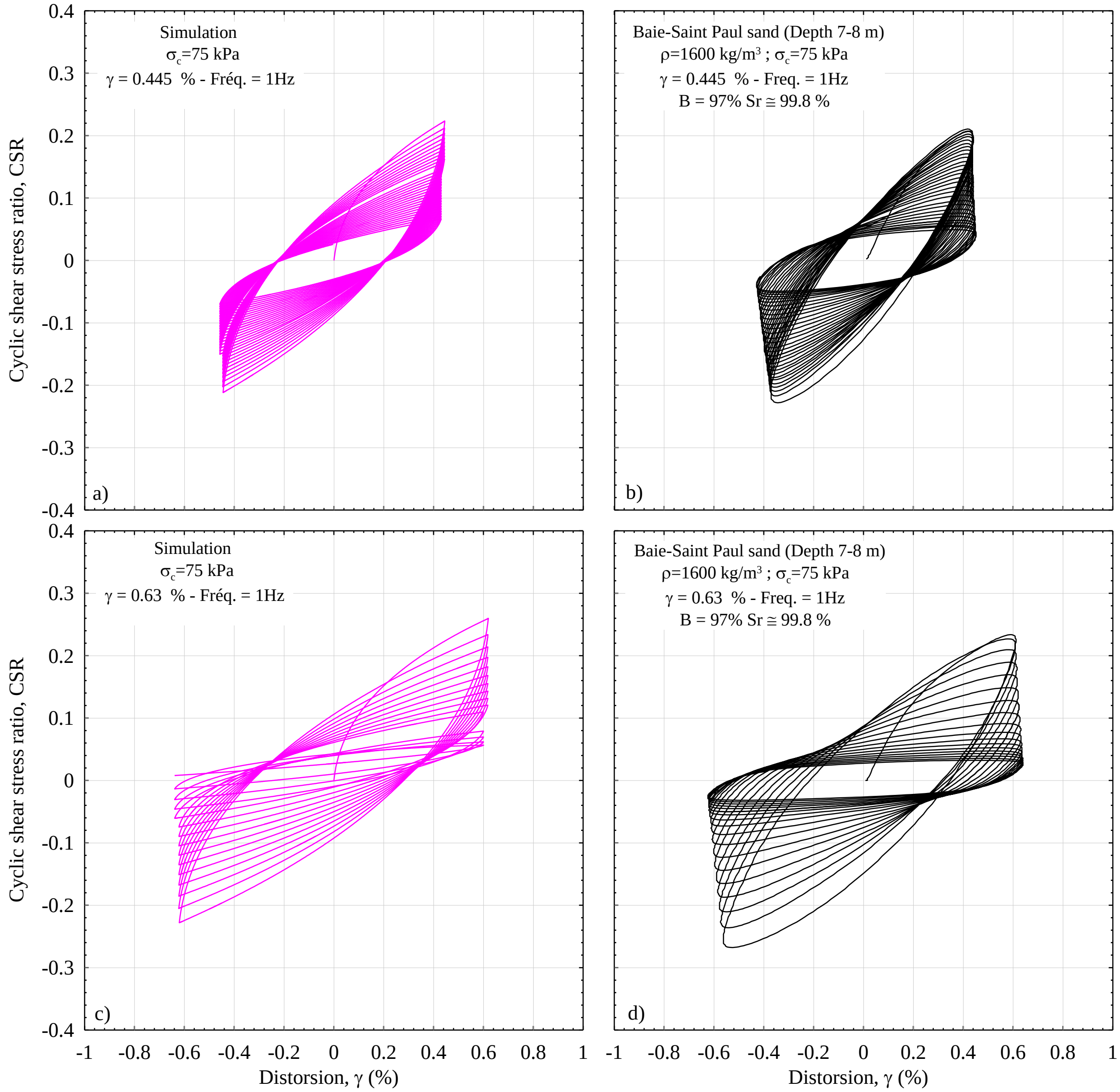

Fig. 10. Comparison between measured and computed CSR-γ_{cyc} loops: (a), (b) γ_{cyc}= 0.445% and (a), (b) γ_{cyc}= 0.63%

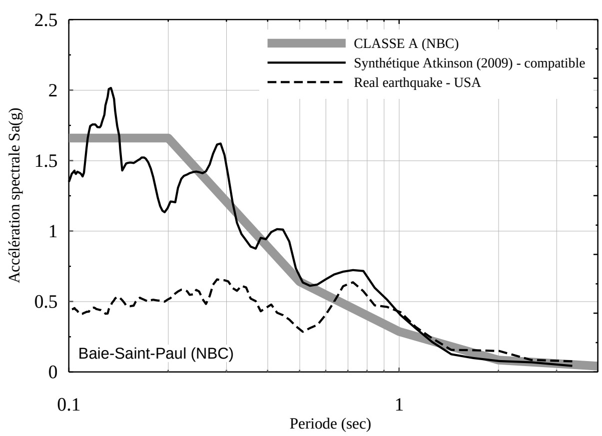

Fig. 11. NBCC 2005 spectrum for Baie-Saint-Paul site on NBCC (A) compared to compatible (Atkinson 2009) and incompatible records

The computed and the measured responses are compared, and a number of useful findings have been emerged:

1. The measured and the computed responses in terms of r_u and CSR are very similar. This similarity confirms the accuracy and reliability of the T_xSS test results as well as the energy-based model adopted in FLAC.
2. The shear distortions presented show filtering effects the earthquake wave experience as it propagates upward.
3. Although the measured and computed CSRs due to the action of the used compatible and incompatible records are the same, the soil is totally liquefied due to the action of the incompatible record, but not liquefied due to the compatible record.

These results, in fact, have two folds impact in the undertaken efforts for evaluation liquefaction potential

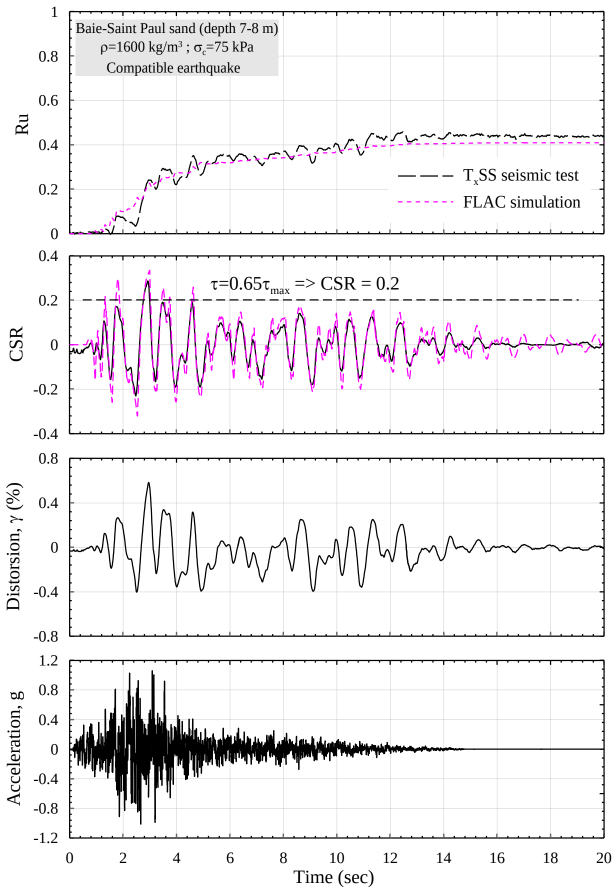

Fig. 12. Measured and computed response of Baie-Saint-Paul sand to a compatible record with NBCC 2005 spectrum

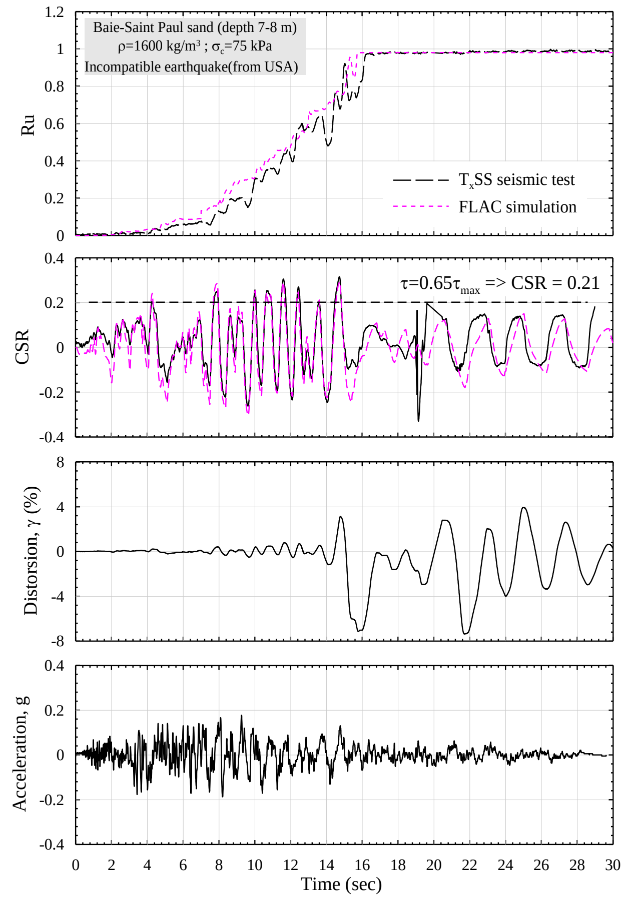

Fig. 13. Measured and computed response of Baie-Saint-Paul sand to an incompatible record with NBCC 2005 spectrum

in the Eastern regions of North America. First they question the use of the stress-based procedures in widely used today. Second, they illustrate clearly that the current charts for liquefaction potential should be revisited.

REFERENCES

Atkinson, G. M. 2009. Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum. Canadian Journal of Civil Engineering, 2009, 36(6): 991-1000, 10.1139/L09-044

Berrill, J.B. & Davis, R.O. 1985. Energy Dissipation and Seismic Liquefaction of Sands: Revised Model. JSSMFE Soils and Foundations 25(2): 106-118.

Chekired, M., Karray, M., and Hussien, M. N. 2015. Experiment setup for simple shear tests in a triaxial cell: T_xSS. Submitted for possible publication in the 68th Canadian Geotechnical International Conference, Quebec, Canada.

Green, R. A., Mitchell, J. K., and Polito, C. P. 2000. An energy-based pore pressure generation model for cohesionless soils. In Proceedings of the John Booker Memorial Symposium–Developments in Theoretical Geomechanics, 16–17 November 2000. Balkema, Rotterdam, the Netherlands. pp. 383–390.

Karray, M., Lefebvre, G. and Ethier, Y. 2011. Relevés MMASW et évaluation du potentiel de liquéfaction au site du couvent de Baie-Saint-Paul. Rapport soumis aux Les Petites Franciscaines de Marie, Géowave Inc., Sherbrooke, Québec, Canada, p. 78.

National Building Code of Canada 2005. National Research Council, Ottawa.

Nemat-Nasser, S., and Shokooh, A. 1979. A unified approach to densification and liquefaction of cohesionless sand in cyclic shearing. Canadian Geotechnical Journal, 16(4): 659678.doi:10.1139/t79-076.

Polito, C., Green, R. A., Dillon, E., Sohn, C. 2013. Effect of load shape on relationship between dissipated energy and residual excess pore pressure generation in cyclic triaxial tests. Canadian Geotechnical Journal, 50(11): 1118-1128.

Seed, H.B., Idriss, I.M., Makdisi, F., and Banerjee, N. 1975. Representation of irregular stress time histories by equivalent uniform stress series in liquefaction analysis. Report No. EERC 75-29, Earthquake Engineering Research Center, College of Engineering, Univ. of California, Berkeley, California, United States.