

# Toward the post-seismic settlement assessment in the laboratory

Aya Bayoumi, Mourad Karray

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

Chekired Mohamed

Hydro-Québec, Montréal, Québec, Canada



The prediction of ground deformations induced by a dynamic activity is becoming widely recognized for the significant impact on structures and lifelines. Evaluation of liquefaction damage has been processed based on standard charts that suffer from a major limitation concerning their dependence on one soil type and its physical parameter (relative density). In an attempt to assess settlement based on the soil dynamic behavior, a unique experimental methodology was established based on two laboratory testing: Triaxial Simple Shear Apparatus (TxSS) and Piezoelectric Ring Actuator Technique (P-RAT). TxSS allows soil testing in two conditions (cyclic and post-cyclic), where all necessary variations regarding soil's strength reduction and resulted volumetric strain can be recorded. Based on a developed TxSS theoretical model, shear wave velocity ( $V_s$ ) of every soil specimen is calculated and later verified using P-RAT measurement. After several tests on Ottawa F-65, it is proved that a correlation exists between energy dissipated from cyclic loading and volumetric strain. A chart is developed based on these parameters where the soil's mechanical property ( $V_s$ ) is a controlling factor. This approach emphasizes the ease of producing a similar chart for any soil based on two laboratory tests and/or by following the specified theoretical correlation.

## RÉSUMÉ

L'importance de l'estimation des déformations des sols induites par une activité dynamique est de plus en plus reconnue pour son impact significatif sur les structures et les installations vitales. L'évaluation des dommages causés par la liquéfaction est effectuée avec des chartes standards présentant une limitation majeure quant à leur dépendance à un seul type de sol et à ses paramètres physiques (densité relative). Dans le but d'évaluer le tassement en se basant sur le comportement dynamique du sol, une méthodologie expérimentale unique a été établie moyennant deux tests au laboratoire : le cisaillement triaxial simple (TxSS) et la technique des anneaux actuateurs piézoélectriques (P-RAT). Le TxSS permet de tester le sol dans deux conditions (cyclique et post-cyclique), où toutes les variations nécessaires concernant la réduction de la résistance du sol et la déformation volumétrique résultante peuvent être enregistrées. Avec un modèle théorique développé et adapté au TxSS, la vitesse d'onde de cisaillement ( $V_s$ ) de chaque échantillon de sol est calculée et vérifiée ultérieurement à l'aide d'une mesure P-RAT. Après plusieurs essais sur le sable d'Ottawa F-65, il a été prouvé qu'il existe une corrélation entre l'énergie dissipée et la déformation volumétrique. Une charte a été établie où  $V_s$  est un facteur déterminant. Cette approche met l'accent sur la facilité à reproduire expérimentalement cette charte pour n'importe quel sol et/ou en suivant les corrélations théoriques spécifiées.

## 1 INTRODUCTION

Studying the post-seismic behavior of soil has been a significant step in predicting the accompanied settlement of superstructures and substructures. In literature, two main categories were considered in such study. The first one was based on soil in-situ investigation methods like N-SPT and CPT. Tokimatsu and Seed (1987) were the pioneers of this category, in which they have conducted settlement charts for dry and saturated soil. Whereas, the second category was based on the factor of safety against liquefaction ( $F_{s_{liq}}$ ). In practice, second category charts such as that of Ishihara and Yoshimine (1992), are being widely used by engineers to estimate the settlement. These charts have been somehow misleading due to their lack of versatility despite their compatibility with a number of real case studies. These charts are based on one soil type (clean uniform sand), which make them not always adequate to being applied on other soil deposits. Charts of both settlement assessment categories involve cyclic amplitude as a load parameter and relative density as a soil physical parameter. These methods have been successively modified and refined (e.g., Shamoto et al.

1996, 1998; Zhang et al. 2002; Wu and Seed 2004; Lee 2007; Cetin et al. 2009; Juang et al. 2013). The most recent settlement assessment was made by Mesri et al. (2017). They have compared their own approach, which was based on the determination of the compressibility coefficient and standard penetration number, with that of Ishihara and Yoshimine 1992 and Tokimatsu and Seed 1987. The comparison does not indicate any similarity for  $F_{s_{liq}}$  less than 1 due to their fine content correction. However, their chart still relies on relative density. Specimens with the same relative density can lead to different dynamic behavior due to the different soil particles rearrangement. In fact, settlement assessment should deal with parameters that reflect the microstructure of the soil and govern this dynamic mechanical behavior. One of the aspects that had been neglected in the previous settlement assessment charts is the deformation induced for  $F_{s_{liq}}$  greater than one. In Ishihara and Yoshimine (1992), charts are proposed for FS up to 2; however, there is no exact estimation beyond 1. The addressed method in this paper will give an accurate calculation of the volumetric strain for  $F_{s_{liq}}$  greater than 1 because soil can undergo deformations even if it does not liquefy.

This method is proposed to tackle the volumetric strain calculation for any soil type based on its shear wave velocity and dissipated energy from the applied load. It is important to perform laboratory experimental testing where both soils' physical and mechanical parameters, along with the dynamic flow in pre-seismic and post-seismic stages are determined. In an attempt to establish a correlation between the volumetric strain, dissipated energy and the soil's mechanical parameter, cyclic strain-controlled undrained testing are performed on Ottawa F-65 sand. These tests are then directly followed by pore pressure dissipation. This paper shows testing results performed by varying relative densities and cyclic amplitudes using the Triaxial Simple Shear Apparatus (TxSS). In addition, direct measurements of shear wave velocity were performed for some tests using the Piezoelectric Ring Actuator Technique (P-RAT).

In this paper, a volumetric strain chart specifically for the Ottawa F65 sand has been elaborated at different factor of safeties and shear wave velocities. It highlights the possibility of conducting the required seismic analysis of any soil deposit. On the other hand, a comparison was made between the proposed method and Ishihara and Yoshimine (1992) method. The comparison results emphasize the importance of establishing a unique settlement assessment chart for each soil type, involving its mechanical parameters rather than just physical parameters.

## 2 EXPERIMENTAL WORK

### 2.1 Experimental Setups

In this paper, 45 tests are performed using the Triaxial Simple Shear Apparatus (TxSS); the main apparatus used to apply the seismic load to soil specimens and study the post-seismic behavior of soil. TxSS is developed and designed by Hydro-Quebec's Research Institute (IREQ) in a collaboration with Université de Sherbrooke. TxSS allows the evaluation of static and dynamic responses and rotation of principal stresses. TxSS ensures also the ability to simulate 3D in-situ conditions. Soil specimens are prepared in a triaxial cell where confinement pressure is applied after saturation is achieved. Specimens can be then subjected horizontally to several types of loading irregular, cyclic or monotonic loading at a specific frequency and cyclic amplitude. Comparing this test to other cyclic tests, TxSS will give a direct measurement of pore pressure rather than the pressure deduction method, which leads to inaccurate results most of the time.

In addition to cyclic and post-cyclic testing of soil specimens, soil's shear wave velocity is measured using the P-RAT. This technique has been developed in the geotechnical laboratory of Université de Sherbrooke (Gamal El-Dean 2007, Ethier 2009, Karray et al. 2015, Mhenni et al. 2015, Mhenni et al. 2016). This technique is composed of two piezoelectric sensors attached to the base and top of an oedometer cell in which one ring serves as an emitter and the other ring serves as a receiver. When the piezoelectric ring sensor is excited, a radial contraction is generated, resulting in pure S-wave propagation through the specimen. With its unique frequency domain method

Table 1. Characteristics of Ottawa F-65 sand

Parameters	Ottawa F-65
D50(mm)	0.217
Cu	1.68
Cc	1.28
$e_{min}$	0.53
$e_{max}$	0.82
Gs	2.668

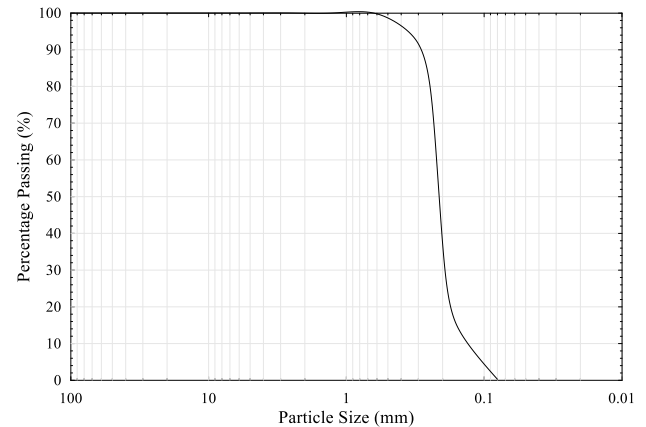


Figure 1. Grain size distribution of Ottawa F-65 sand.

analysis, a phase shift correction can lead to the true shear wave velocity measurement without any subjective interpretation with other time domain method analysis. For further details, Karray et al. (2015) summarize 10 years of P-RAT development.

### 2.2 Experimental Methodology

Ottawa F65 sand is used in this study because it is a uniform clean sand as shown according to the grain size distribution and physical properties in Figure 1 and Table 1, respectively. Uniform clean sand is used in this proposed method in order to compare results with the previous methods that use same type of soil. Moist sand is placed in 3 layers where every layer is compacted until the initial desired density is reached. Soil specimens with a diameter-height ratio (D/H) equals to 3.6 were prepared at three different dry densities (1500, 1580, 1650 kg/m<sup>3</sup>) enclosed in an elastic membrane. These specimens are set to be saturated to have a minimum of 0.97 Skempton's B coefficient. Then, they are isotropically consolidated to a 100 kPa confinement pressure. At each relative density, strain-controlled cyclic tests are performed at a frequency 1 Hz by fixing the cyclic amplitude while varying the number of cycles. Cyclic tests are performed in undrained conditions where excess pore pressure generation ( $R_u$ ) is directly recorded using the TxSS. Soil samples are considered liquefied when  $R_u$  reaches 0.9. In addition, the variation of cyclic stress ratio (CSR) as a function of the shear strain ( $\gamma$ ) is obtained in the form of hysteresis loops.

The generated pore pressure is set to be dissipated when drained conditions are permitted. In parallel, the pore pressure dissipation ratio ( $\Delta u$ ) is recorded with the

dissipated water's flowrate, which is measured via a flowmeter. In fact, the dissipated volume is then precisely calculated and the volumetric strain is deduced (Bayoumi et al., 2018). As for the shear wave velocity ( $V_s$ ) measurement, series of soil specimens were prepared in oedometric cell at low and high relative densities (1400 kg/m<sup>3</sup> and 1680 kg/m<sup>3</sup>). Direct measurement of  $V_s$  has been determined for these samples by the P-RAT technique while performing the oedometric tests. Normalized shear wave velocity ( $V_{s1}$ ) is obtained as a function of the corresponding varying void ratio for each test.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Volumetric Strain-Dissipated Energy Chart

As a preliminary trial to determine the volumetric strain induced by a seismic activity using the proposed experimental method, 45 tests were performed on TxSS. The choice of parameters governing the settlement assessment in the addressed method was based on several experimental observations. As stated in the introduction, the charts that tackle the liquefaction-induced settlement suffer from limitations. One of them considers physical soil parameters only (i.e. Relative density) while another relies on the cyclic amplitude as a load parameter. In order to overcome these limitations, and with the opportunity of obtaining at the same time all the necessary varied parameters, two main parameters were chosen to be involved in this approach.  $V_s$  is the soil mechanical parameter chosen. The other parameter is a load parameter which is dissipated energy in the soil specimens during the cyclic loading since it is as a function of both CSR and cyclic shear strain.

During the cyclic load, the excess pore water pressure is directly recorded. As shown in Figure 6, CSR is obtained as a function of shear strain ( $\gamma$ ) in the form of hysteresis loops. The dissipated energy is calculated by the area bounded in the hysteresis loops. In fact, the maximum shear modulus ( $G_{max}$ ) can be estimated from the obtained hysteresis loops by applying the calibrated Sig 4 (Chehat et al., 2018) model for TxSS results. As a result, the normalized shear wave velocity ( $V_{s1}$ ) for each tested soil specimen can be estimated.  $V_{s1}$  for each TxSS test is plotted as a function of its corresponding void ratio in Figure 2. For further verification of these estimated  $V_{s1}$  values, direct measurements were obtained by P-RAT as described in previous sections. Figure 2 shows that the P-RAT results fit the curve confirming the accuracy of the estimated  $V_{s1}$ . After the cyclic load, the post-seismic volume change is recorded in drained conditions where the volumetric strain is calculated precisely. As a result of these experiments, a chart was produced for Ottawa F65 sand showing the variation of the volumetric strain as a function of the dissipated energy according to four normalized shear wave velocity categories (from less than 140 m/s and reaching 230 m/s). Figure 3 reveals that each  $V_{s1}$  category corresponds to a unique relation between volumetric strain and dissipated energy. For each relative density, the cyclic amplitude is fixed and the number of cycles were varied, in order to obtain various  $R_u$ . For

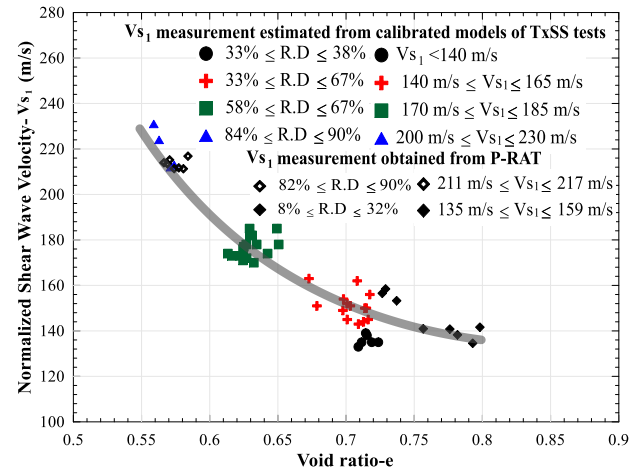


Figure 2. Variation of normalized shear wave velocity as a function of void ratio for all TxSS and P-RAT results

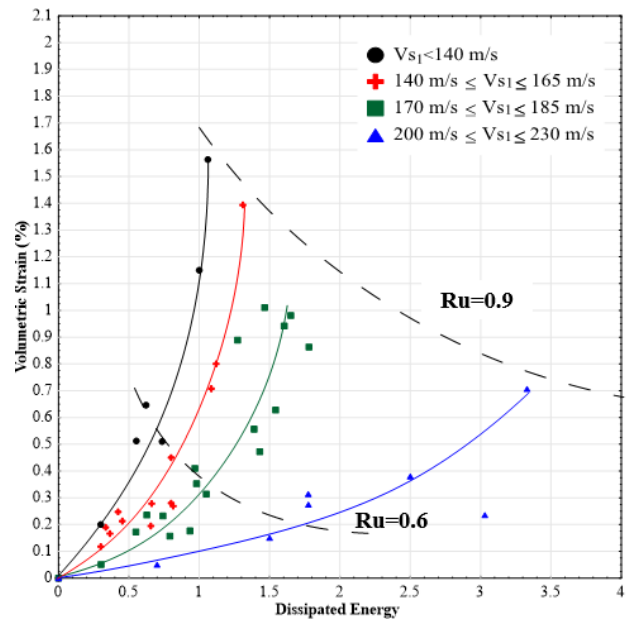


Figure 3. Volumetric strain-dissipated energy chart for Ottawa F65 sand

$R_u \leq 0.6$ , as the cycles number increases, the dissipated energy and volumetric strain increase gradually. For  $0.6 \leq R_u \leq 0.9$ , the trend increases sharply. In Figure 3, there are no results beyond  $R_u = 0.9$ , but it is supposed that deformations will reach a steady state when  $R_u > 0.9$  based on the initial soil state.

#### 3.2 Comparison with Ishihara and Yoshimine (1992)

The relation between volumetric strain induced by a seismic load and the dissipated energy was already shown in Bayoumi et al. (2017). The chart introduced in the paper of Bayoumi et al. 2017 was made for several soil types (CF-16, CF-6B, and Champlain silt) where all the results correspond to the liquefied state. It is shown that each soil

of these three soils has its own trend concerning this relation. As a result, it is proven that the grain size distribution and the permeability can influence this relation. As permeability decreases, the volumetric strain will decrease and the soil can require more energy to reach liquefaction. For each soil type, the relative density was varied and it is noticed that high relative density can yield to low volumetric strain and vice versa.

The zone below  $R_u=0.9$  in Figure 3 is considered experimentally challenging as proved by several studies that failed to estimate the exact volumetric strain in this zone. In order to have a clear trend in this zone, more tests should be performed. At  $R_u=0.9$ , which is equivalent to a factor of safety against liquefaction ( $F.S_{liq}$ ) equals to 1, a preliminary comparison was made with Ishihara and Yoshimine results at  $F.S_{liq}=1$ . In Ishihara and Yoshimine 1992 study, Fuji river sand was used. This sand type is also uniform clean sand as Ottawa F65. According to Figure 4, it is obviously shown that there is a compatibility of the proposed method with that of Ishihara and Yoshimine 1992 method for all relative densities except for the lowest one. This result is expected at the loose state even if the two sands are uniform clean sands, their  $e_{min}$  and  $e_{max}$  differ. As a result, different deformations will occur at the loose state.

In such cases, depending on the soil physical parameter in the assessment can lead to incorrect estimation of the settlement. Incorporating a mechanical soil parameter (shear wave velocity) can lead to a better estimation of the deformation especially that it can reflect the microstructure of the soil, rather than just the state.

Ishihara and Yoshimine chart can serve as a good estimation for clean uniform sand, but not for other soil types. The chart introduced in Bayoumi et al., 2017 confirms this aspect. The results of Ottawa F65 for  $F.S_{liq}=1$  are added to this chart as shown in Figure 5. Each soil type imposes a unique trend in volumetric strain-dissipated energy relation. Consequently, estimating settlement for a soil deposit cannot be achieved by relying on charts that are related to clean sand.

#### 4 CONCLUSIONS AND RECCOMENDATIONS

This paper introduces a proposed experimental approach to determine the settlement induced by seismic load based on its dissipated energy. This approach is characterized by eliminating some of the limitations that are present in some previous studies. In addition to the fact that these studies are mostly made for just one soil type, they are based on the use of relative density as a soil physical controlling parameter rather than dealing with parameters that control the dynamic mechanical behavior of the soil like shear wave velocity. The proposed method can lead to an exact estimation of volumetric strain when soil undergoes any deformation regardless of the factor of safety against liquefaction. This experimental approach is mainly composed of performing the cyclic test in undrained conditions and then permitting drainage to allow the dissipation of the generated pore pressure using the Triaxial Simple Shear Apparatus TxSS). While dissipation, the dissipated water volume is recorded via a flowmeter and the volumetric strain is calculated. 45 strain controlled

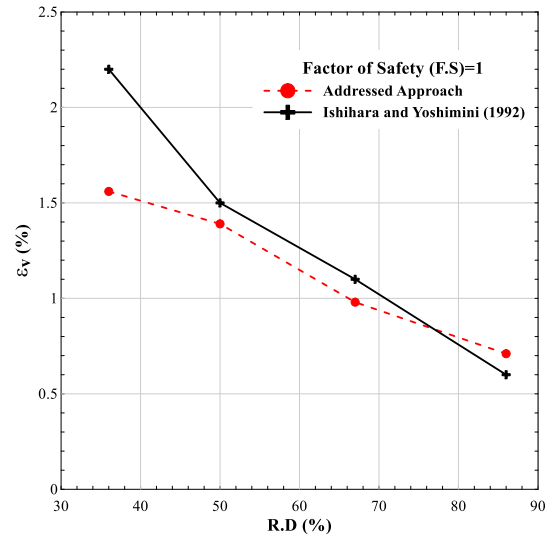


Figure 4. The variation of volumetric strain as a function of relative densities for each of the addressed method and Ishihara and Yoshimine 1992 method at a Factor of safety=1

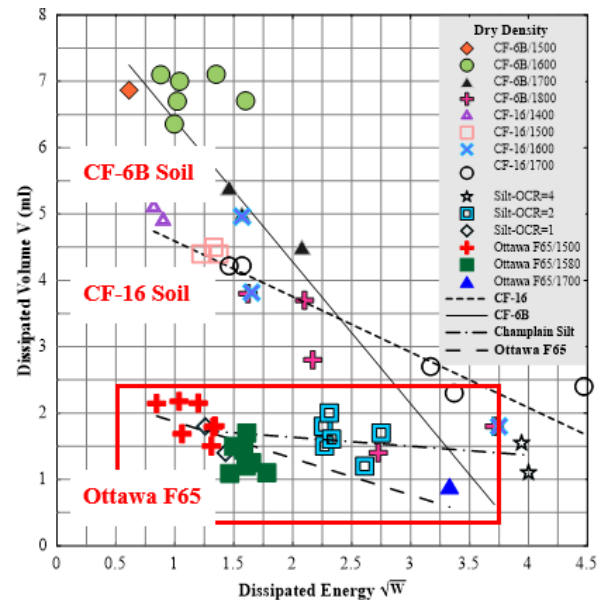


Figure 5. Variation of the dissipated volume as a function of dissipated energy for CF-6B sand, CF-16 sand, Champlain silt and Ottawa 65 sand (Bayoumi et al., 2017)

tests were conducted on Ottawa F65 sand at several densities and varying cyclic amplitude and number of cycles. Using the calibrated Sig 4 (Chehat et al., 2018), shear wave velocity can be estimated for every TxSS test and can be verified by direct measurement using the P-RAT technique. A chart that reveals the variation of the volumetric strain as a function of the dissipated energy, was produced specifically for Ottawa F65 sand according to four different ranges of shear wave velocity. It is concluded that settlement assessment of any soil type can

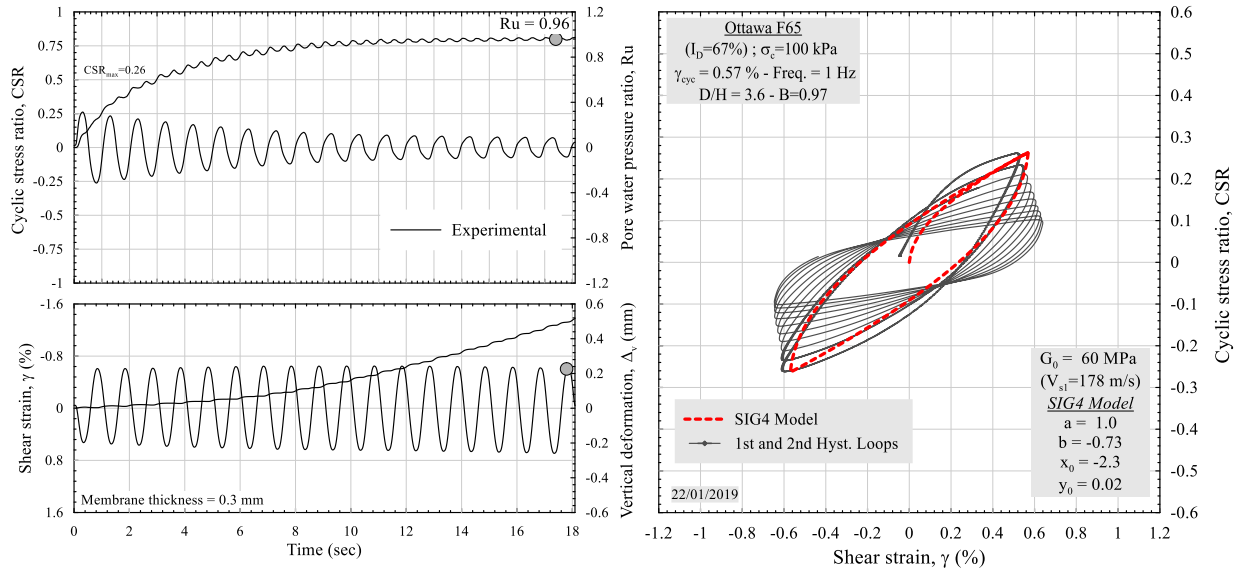


Figure 6. TxSS Records of CSR variation and pore pressure generation of Ottawa F65 sand

be achieved by following the proposed method, which is based on determining a load parameter (dissipated energy) and soil mechanical parameter (shear wave velocity). As a preliminary trial, this method is established experimentally. However, with advanced steps, testing several soil types and building a calibrated numerical model can lead to a theoretical correlation.

In order to establish a good correlation, further analysis should be done on varying loading and soil physical and mechanical properties (cyclic amplitude, frequency, relative density, shear wave velocity...). In fact, the application of two laboratory testing, such as TxSS and piezoelectric ring-actuator technique (P-RAT) to determine the post-seismic behavior and shear wave velocity respectively, can simply lead to seismic-induced settlement assessment in the laboratory.

#### ACKNOWLEDGEMENT

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and HydroQuebec for their financial support throughout this research project.

#### REFERENCES

- Bayoumi, A., Karray, M. and Chekired, M. 2018. Measurement of hydraulic conductivity variation in post seismic behavior of sand using TxSS, *GeoEdmonton 2018*, Edmonton, AB, Canada.
- Bayoumi, A., Karray, M., Hussein, M. and Chekired, M. 2017. Use of TxSS Test for Assessment of Post Seismic Behavior of Soil, *GeoOttawa 2017*, Ottawa, ON, Canada.
- Cetin, K., Bilge, H., Wu, J., Kammerer, A. and Seed, R. 2009. Model for Probabilistic the Assessment of Cyclically Induced Reconsolidation (Volumetric) Settlements, *Journal of Geotechnical and geoenvironmental Engineering*, 2009, 135(3): 387-398.
- Chekired, M., Lemire, R., Karray, M. and Hussein, M. 2015. Experiment Setup for simple shear tests in a triaxial cell: TxSS, *GeoQuebec 2015*, Quebec City, QC, Canada.
- Chiaradonna, A., Bilotta, E., D'Onofrio, A., Flora, A. and Silvestri, F. 2018. A Simplified Procedure for Evaluating Post-Seismic Settlements in Liquefiable Soils, *Geotechnical Earthquake Engineering and Soil Dynamics V GSP 290*: 53-59.
- Chehat, A., Hussein, M., Abdellaziz, M. and Karray, M. 2018. Stiffness-and damping-strain curves of sensitive Champlain clays through experimental and analytical approaches, *Canadian Geotechnical Journal* 56(3): 364-377.
- Ethier, Y.A. 2009. *La mesure en laboratoire de la vitesse de propagation des ondes de cisaillement*, Thèse de doctorat en génie civil, université de Sherbrooke, QC, Canada.
- Gamal El-Dean, D. 2007. *Development of a new piezo-electric pulse testing device and soil characterization using shear waves*, Thèse de doctorat en génie civil, université de Sherbrooke, QC, Canada.
- Green, R. A., Mitchell, J. K., and Polito, C. P. 2000. An energy-based pore pressure generation model for cohesionless soils. *Proceedings of the John Booker Memorial Symposium Sydney*, New South Wales, Australia, A.A. Balkema Publishers, Rotterdam, Netherlands.
- Ishihara, K. and Yoshimine, M. 1992. Evaluation of Settlements in Sand Deposits Following Liquefaction during Earthquakes, *Soils And Foundations*, Vol. 32 No. 1 P 173-188.

- Juang, C. H., Ching, J., Wang, L., Khoshnevisan, S. and Ku, C.-S. 2013. Simplified procedure for estimation of liquefaction-induced settlement and site-specific probabilistic settlement exceedance curve using cone penetration test (CPT), *Canadian Geotechnical Journal* 50(10): 1055-1066.
- Karray, M., Ben Romdan, M., Hussein, M. and Ethier, Y. 2015. Measuring shear wave velocity of granular material using the piezoelectric ring-actuator technique (P-RAT), *Canadian Journal of Geotechnics*, 52 (9): 1302-1317.
- Lee, C.Y. 2007. Earthquake-induced settlements in saturated sandy soils, *ARNP Journal of Engineering and Applied Sciences*, 2(4): 6–13.
- Lenart, S. 2008. *Earthquake Engineering: New Research, The use of dissipated energy at modeling of cyclic loaded saturated soils*, Chapter in Advances in Environmental Research January 2008, Nova Science Publishers, Inc.
- Mhenni, A., Hussein, M., Karray, M. and Ethier, Y. 2015. Improvement of the Piezo-electric Ring Actuator technique (P-RAT) using 3D numerical simulations, *GeoQuebec 2015*, Quebec City, QC, Canada.
- Mhenni, A., Hussein, M., Karray, M. and Ethier, Y. 2016. Versatility of the P-RAT for shear wave velocity Measurement, *GeoVancouver 2016*, Vancouver, BC, Canada.
- Shamoto, Y., Zhang, J.M., and Tokimatsu, K. 1998. Methods for evaluating residual post-liquefaction ground settlement and horizontal displacement, *Soils and Foundations*, Special Issue 2, pp.69-83.
- Shamoto, Y., Sato, M. and Zhang, J.M. 1996. Simplified estimation of earthquake-induced settlements in saturated sand deposits, *Soils and Foundations*, 36(1), pp.39-50.
- Tokimatsu, K. and Seed, H.B. 1987. Evaluation of settlement in sands due to earthquake shaking, *Journal of Geotechnical Engineering*, ASCE, 113(8), pp.861-878.
- Wang, B., Zen, K., Chen, G.Q., Zhang, Y.B and Kasama, K. 2013. Excess Pore Pressure Dissipation and Solidification after liquefaction of Saturated Sand Deposits, *Soil Dynamics and Earthquake Engineering*, 49 (2013) 157-164.
- Wu, J. and Seed, R. B. 2004. Estimating of liquefaction-induced ground settlement case studies, *5th Int. Conf. on Case Histories in Geotechnical Engineering*, Paper 3.09, New York, USA.
- Yi, F. 2010. Procedure to evaluate liquefaction-induced settlement based on shear wave velocity, *9th US National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, Toronto, ON, Canada.
- Zhang, G., Robertson, P.K. and Brachman, R.W.I. 2002. Estimating liquefaction-induced ground settlements from CPT for level ground, *Canadian Geotechnical Journal*, 39: 1168–1180.