Shear modulus and damping ratio curves of sensitive Eastern Canadian clays in cyclic simple shear triaxial test

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ABSTRACT

The shear modulus and equivalent viscous damping ratio are important parameters to assess the dynamic response of soil deposits. Cyclic simple shear triaxial tests were carried out to assess the normalized shear modulus reduction and damping curves of sensitive Eastern Canadian clays at cyclic shear strain of about 0.001%-3% using a new seismic simulator T_xSS. The samples were consolidated under similar in-situ effective stress conditions and the cyclic loading was sinusoidal strain-controlled mode. The T_xSS tests provide accurate monitoring of confinement and pore pressure conditions. P-RAT tests were used to validate the shear modulus at very small shear strain. A comparison between the obtained curves and literature curves show some differences, especially on the equivalent viscous damping ratio curves. The differences may be attributed to the differences between T_xSS conditions and other devices conditions (e.g., DSS, Triaxial, Resonance column, Bender element) in addition to the differences in geotechnical properties between sensitive eastern Canadian clays and other clays. The G/G_{max}-γ and ξ-γ curves were then used in a one-dimension numerical simulation to assess the dynamic response of natural clays deposits. The results show a significant difference in the maximum acceleration and spectral acceleration of the clay deposits.

Keywords: Earthquake, Clay, Damping, Modulus, T_xSS

INTRODUCTION

In eastern Canada, sensitive clays cover a large part of the area where 90% of the population lives. Known also as Leda clay, sensitive clay of eastern Canada is characterized by a high sensitivity and its tendency to transform from stiff material to liquid when it is remoulded [1].To take account the particularity of this soil, the National Building Code of Canada in its recent version (2005, 2010) introduce a new class of soil named class F where is included quick and highly sensitive clays. Leroueil et al. [2] reported that the values of the sensitivity of Eastern Canada clays are rarely below 15. According to the NBCC [3], the deposits classified F required a specific geotechnical investigation and dynamic site response analysis. Such an analysis could assess the amplification motion of the deposits and its effect on the structures. Several authors pointed out that soft soil deposits could lead to high amplification of ground motions. Kramer [4] reported several historical cases where due to the presence of soft soil deposits, the ground motions were highly amplified and caused pronounced damage. According to Kramer [4], the reason of such amplification is the "*double resonance condition: amplification of the bedrock motion by the soil and amplification of the soil motion by the structure*". On other hand, the seismic activity in eastern Canada is concentrated along the St. Lawrence Valley where the majority of sensitive clays deposits exists (Sea Champlain clays). Therefore, these sensitive clays are subjected to seismic loading. Thus, the assessment of the dynamic parameters of sensitive clays become necessary in order to accurately assess their dynamic response.

Several efforts have been made in the last decades to understand the dynamic behavior of sensitive clays. For example, Lee [5] performed cyclic triaxial tests on sensitive Outarde clay and concluded that the failure occurs in a thin well-defined shear plane where the clay is reduced to liquid. Javed [6] studied the cyclic behavior of Rigaud clay and reported that the increase of sensitivity increases the loss of strength of the sensitive clay under cyclic loading. Rahhal [7] investigated the modulus reduction and damping curves on Saint-Alban clay and concluded that sensitive Champlain clay behaves more linearly comparing to other clays. The same conclusion has been made by Chahde [8] and Warde [9]. On other hand, the previous studies of shear modulus reduction and damping curves on sensitive Champlain clays were based on resonant column test which limited the investigation of the G/G_{max}-γ and ξ-γ curves from small to medium shear strain (about 0.1%). Recently (in 2015) a new triaxial simple shear apparatus (T_xSS) has been developed at Sherbrooke University and Research Institute of Hydro-Quebec (IREQ). The T_xSS is able to investigate the stress-strain curve of the soils for a wide range of shear strain from 0.001% to about 3%.

The conception, Characteristics and the advantages of T_xSS apparatus are fully described in Chekired et al. [10] and the procedure for the stress-strain curve used in this study is summarized in section of testing program.

This paper presents a series of cyclic T_xSS and P-RAT results carried out on very sensitive Beauharnois clay to assess: the (*i*) maximum shear modulus (*ii*) modulus reduction curve (*iii*) damping curve. The results were examined and compared to the literature models. Finally, a numerical simulation was carried out to investigate the effect of the difference in the modulus reduction and damping curve between experimental data and literature models.

DESCRIPTION OF THE SITE AND SOIL CONDITIONS

The soil used in this study is a post-glacial sensitive clay from Beauharnois. Beauharnois is a municipality in the southeast of Montreal. The clay was sampled using Shelby tube. Table 1 present the geotechnical properties of Beauharnois clay. Beauharnois clay is characterized by liquid limit 57%, plastic limit 30%, and liquid index 1.7. The undisturbed shear strength measured on T_xSS test is 35 kPa and the sensitivity measured by fall cone test is higher than 500.

Table 1: Geotechnical properties of investigated clay

Clay	Depth (m)	w_N (%)	I_p (%)	I_L (%)	σ'_p (kPa)	S_u (kPa)	S_t	Clay content (%)
Beauharnois	12.4	76	27	1.7	160	35	>500	75

TESTING PROGRAM

After sampling, the soil was extruded from the tube sampler and sealed using household plastic wrap and a wax compound prepared from a mixture of paraffin and Vaseline. The samples were then subjected to the standard characterization tests (Swedish fall cone, sedimentation, specific density G_s, Atterberg limits). The oedometer test was carried out following the standard [11]. In parallel to the oedometer test, measurements of the shear wave velocity of the clay were taken by using P-RAT technique. The procedure for the P-RAT measurement is described in [12] and [13]. The maximum shear modulus was then calculated using the following Eq (1):

$$G_{max} = \rho_T . V_s^2 \tag{1}$$

The triaxial simple shear apparatus was used to study the cyclic stress-strain curve of Beauharnois clay. The use of the T_xSS apparatus in such measurements has two principal advantages: first, the continuity between the small and large shear strain measurements and therefore the scattering is reduced. The second advantage is that the T_xSS can provide a direct measurement of the pore pressure build-up during the tests which is more accurate than using the constant volume principle ([15], [16]). The preparation of the T_xSS test follows the almost same procedure for the standard triaxial test [14]. The clay was carefully cutted to obtain specimens with 62 mm diameter and 25 mm height. The specimens were then put in the triaxial cell, saturated and consolidated to the in-situ effective mean stress. The cyclic tests were carried out with a frequency of 1 Hz which is compatible with the seismicity of eastern Canada. The cyclic T_xSS tests were used to calculate the secant shear modulus and an equivalent damping ratio. These two parameters were calculated from the hysteresis loop obtained by applying a horizontal displacement on the top of the specimen. Six cycles of a sinusoidal signal of shear strain were applied to the specimen. A friction test was carried out after each T_xSS test and the final stress-strain curve is calculated by removing the friction stress of the apparatus from the initial test. The secant shear modulus is obtained by taking the average of secant shear modulus of the six cycles. The equivalent damping ratio was calculated from the area inside the loop for each cycle following Eq (2):

$$\xi = \frac{A}{2\pi G \gamma_c^2} \tag{2}$$

Where G is the secant shear modulus, A is the area inside the loop, and γ_c is the shear strain applied for the cycle.

EXPERIMENTAL RESULTS

The results of one-dimensional consolidation and piezoelectric ring actuator test are presented in figure 1. Figure 1-a present the σ'_v-e curve and figure 1-b present the V_{s-1}/ocr^{α}-e curve. The σ'_v-e curve shows that the preconsolidation pressure is clearly defined at effective vertical stress of 160 kPa. The measurements of the shear wave velocity were used to construct the e-V_{s1}-ocr correlation. The curve e- V_{s-1}/ocr^{α}-e show that the normalized shear wave velocity increase with the decrease of the void ratio and increase with the increase of the over-consolidation ratio. The following correlation can be proposed for sensitive Beauharnois clay:

$$V_{s1} = 125 OCR^{0.15} e^{-0.45} \tag{3}$$

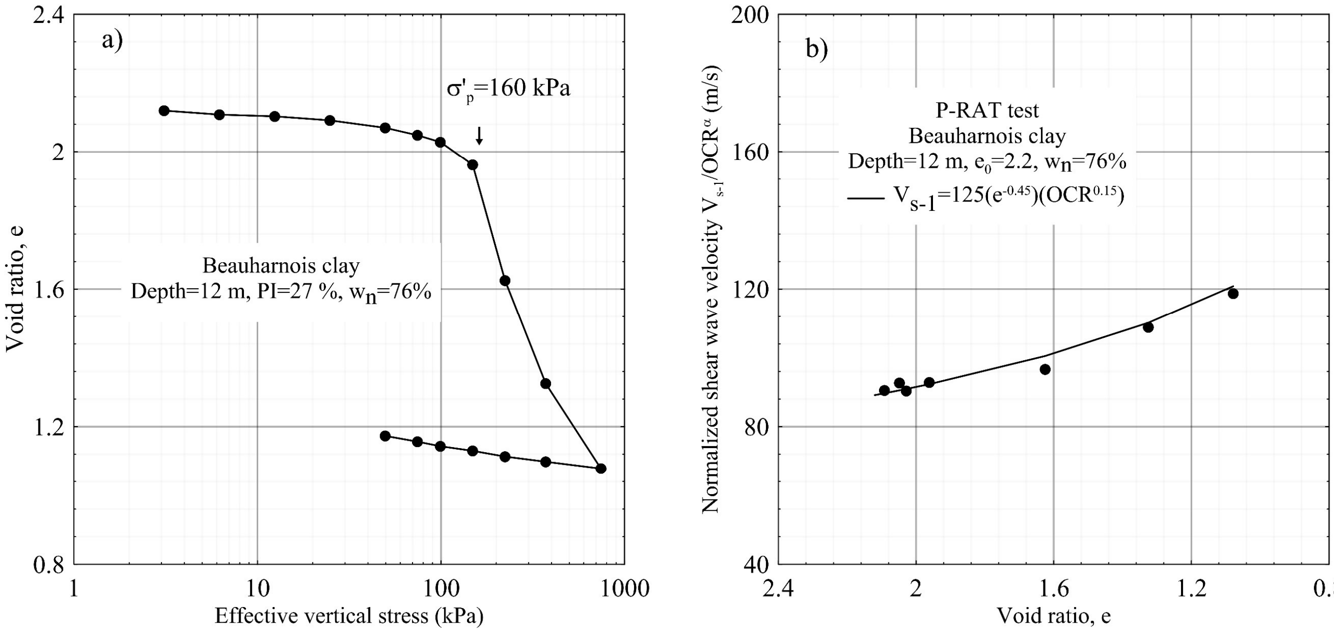

Figure 1 : a) One-dimensional consolidation curve b) normalized Shear wave velocity-void ratio relationship

The experimental results of the triaxial simple shear tests are presented in figure 2 and figure 3. Several strain-controlled tests were carried out with maximum shear strain amplitude ranging between 0.003% and 1.4%. Figure 2 presents the modulus reduction and damping curves of Beauharnois clay. Figure 3 presents the stress-strain curves of different tests. As it can be seen for the test with small maximum shear strain, the hysteresis curve shows small energy dissipated until γ_c=0.2% where the hysteresis curve changes the form and the energy dissipated increase significantly. The G/G_{max}-γ curve show that until γ_c=0.01% the secant shear modulus is almost equal to G_{max}. After γ_c=0.01, the secant shear modulus starts to decrease and reach 68 % at γ_c=0.1 % and 34 % at γ_c=1 %. The ξ-γ curve shows that at γ_c=0.1% the damping ratio is equal to 2.1%. At 0.01% < γ_c < 0.2% the damping ratio increase slightly and reach around 5% at γ_c=0.2%. At 0.2% < γ_c < 0.5% the damping ratio increase rapidly and reach around 9% at γ_c=0.5%. For γ_c > 0.5% it was observed that the damping ratio remain approximately constant with an average value of 9 %.

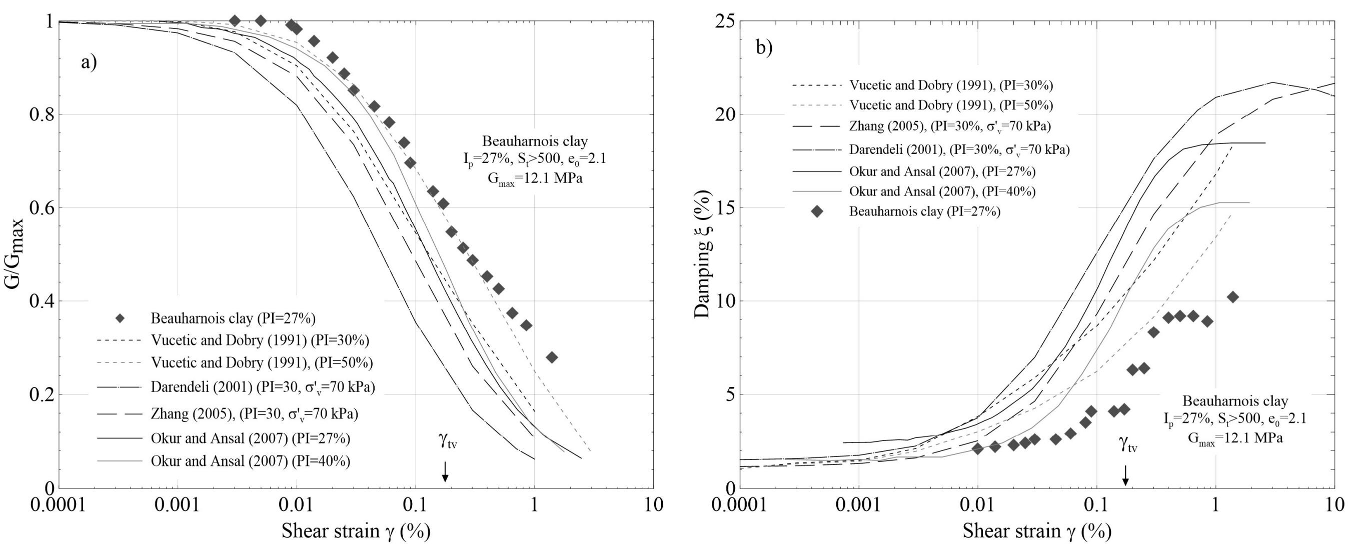

Figure 2: a) Relation between G/G_{max} and γ_c, b) relation between ξ and γ_c

For the comparison purpose, several models of modulus reduction and damping curves were plotted in figure 2. Vucetic and Dobry [17], Darendeli [18], Zhang [19] and Okur and Ansal [20] models were chosen due to the fact that they are the most used models in geotechnical earthquake engineering. For Vucetic and Dobry [17] which is based only on the plastic index, the curves of PI=30% and PI=50% was chosen. For Darendeli [18] model, the following parameters were chosen: σ'_v=70 kPa, frequency=1Hz, PI=27%, OCR=2. Zhang [19] model was drawn by using: σ'_v=70 kPa, PI=27% and Quaternary soil were chosen as geological age. For Okur and Ansal [20], the curves of PI=27% and PI=40% were chosen. The comparison of the G/G_{max}-γ curve obtained experimentally in the T_xSS with the literature models show clearly that the Beauharnois clay curve is higher than the literature models curves. The same observation was made for the damping ratio ξ-γ curve of Beauharnois clay where it was observed that the damping obtained in T_xSS with Beauharnois clay is lower than the damping ratio curve of the literature models.

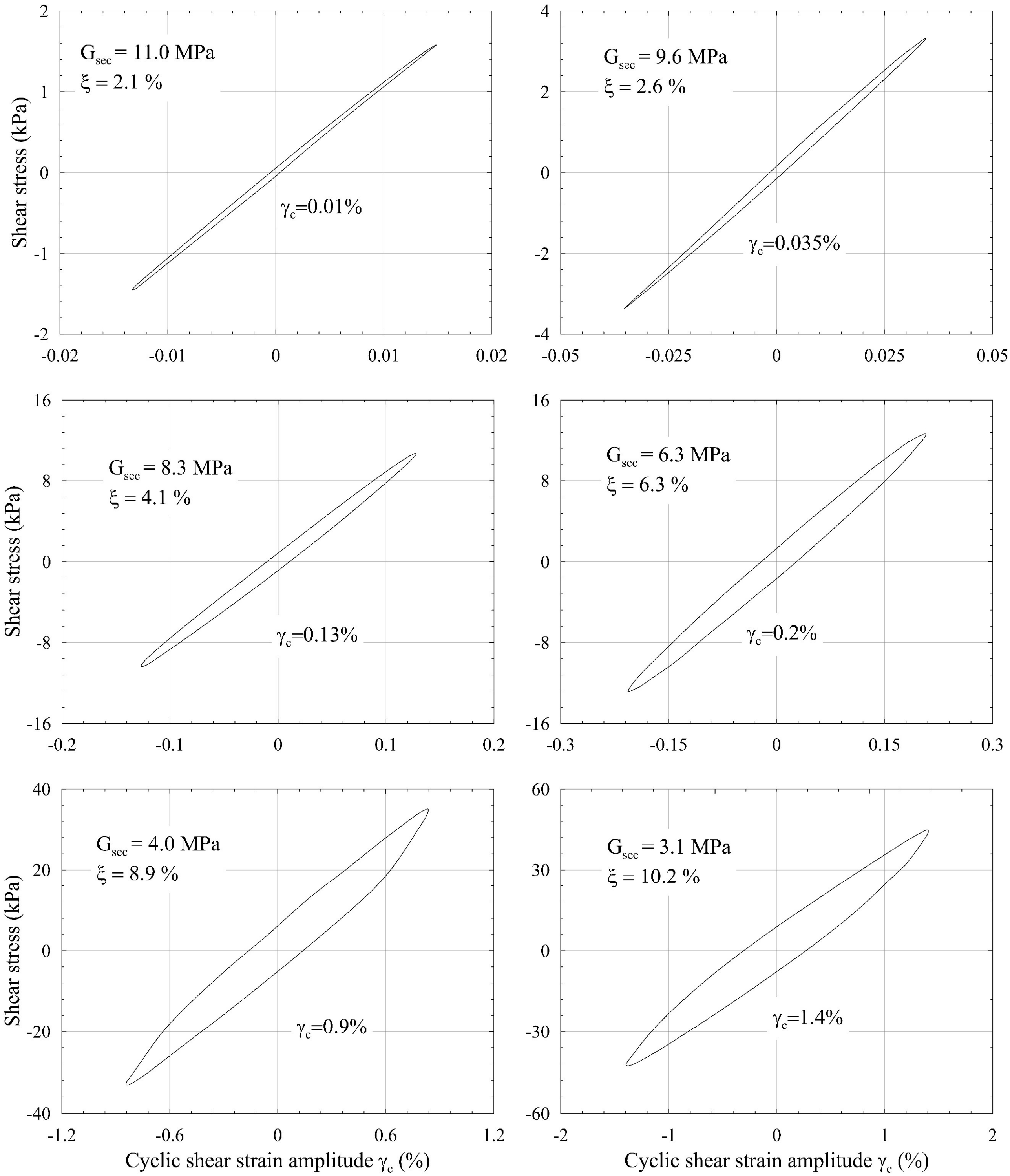

Figure 3: Cyclic stress-strain curve at a different shear strain

More particularly, the comparison with Vucetic and Dobry [17] model shows that the experimental results match well with the reference curve of clay with PI=100%. For Darendeli [18] model, the experimental curve can match with the curve of PI=200%. The same observation can be made for Zhang [19] model. However, as the last two models are based on several parameters (effective vertical stress, OCR, frequency...etc.), other curves can match by changing the other parameters than PI. It should be noted that Okur and Ansal [20] results show the same shape of the damping ratio curve at large deformation as the Beauharnois clay where the damping remains constant contrary to other models (e.g., [17]; [19]). According to Chehat et al. [21], the observed behavior of the damping ratio at large deformation is related to the pore pressure generation. Moreover, the measurements of the pore pressure indicate that the pore pressure starts build up at γ_c=0.2%. Thus, as Okur and Ansal [20] results were obtained on the triaxial apparatus, the generation of pore pressure may explain this observed behavior.

APPLICATION OF MODULUS REDUCTION AND DAMPING CURVES

One-dimensional numerical analysis using two different G/G_{max}-γ and ξ-γ curves on clayey deposit was carried out to investigate the effect of the difference between the curves on the dynamic response of the soil deposit. For the purpose of simplifying the simulation, a simple deposit was chosen composed of a uniform clay layer of about 10 m, overlie a till layer of about 3 m which continues till the bedrock. This stratigraphy is typical for eastern Canada clayey deposits [22]. Figure 4 presents the geotechnical profile used in this simulation. The clay layer has a plastic index of 30 % and a density of 1600 kg/m. The shear wave velocity has a uniform profile on clay layer with V_{s1} of about 100 m/s on the clay layer and 150 m/s on the till layer. V_s of 1500 m/s were taken for the bedrock. The geotechnical profile was divided into several layers of 1 meter. A linear equivalent method implemented in the software Deepsoil version 6.1 was used in this study [23]. Two seismic signals were used in this study: the first signal (accelerogram A) was recorded signal of Saguenay earthquake 1988 at Baie-Saint-Paul station, the second signal (accelerogram B) was a synthetic signal. It should be noted that such signals are compatible with the seismic activity of eastern Canada. The spectral acceleration of the two signals were scaled on the National Building Code of Canada [3] design spectra of the Beauharnois area for site class A [24]. Two models of G/G_{max}-γ and ξ-γ curves were used in the simulation: Vucetic and Dobry [17] and experimental curves determined in this study. The G/G_{max}-γ and ξ-γ curves of the till layer were modelized by using Seed and Idriss [25] mean curves for cohesionless soils. The accelerograms were applied at the bottom of the profile and elastic half-space properties were used for the bedrock.

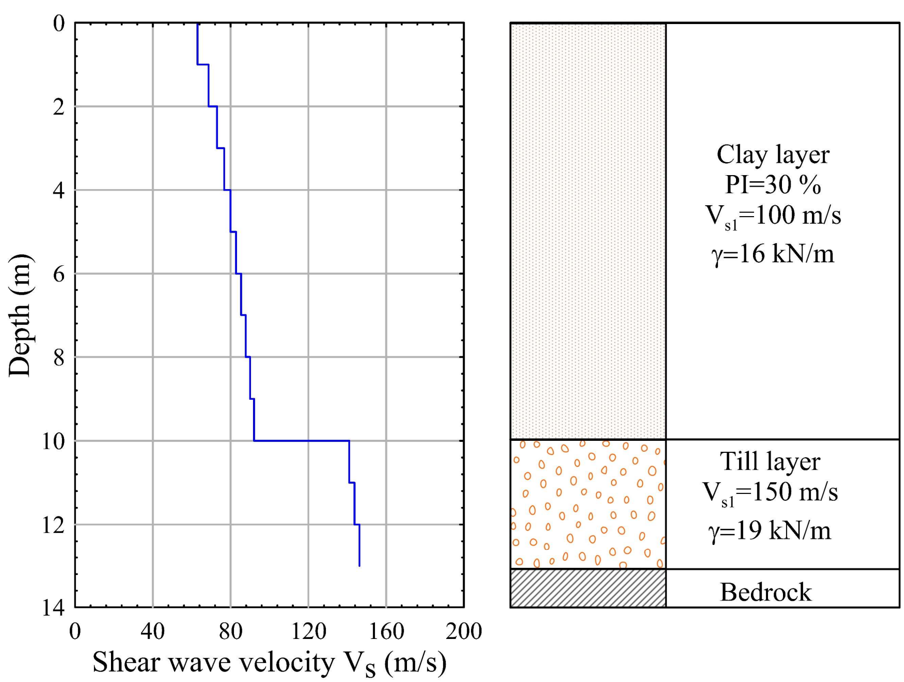

Figure 4: Geotechnical profile used for numerical simulation

The results of the numerical simulation are presented in figure 5. Figure 5b-1 and 5b-2 present the obtained peak ground acceleration profiles. The four PGA profile shows that there is an amplification at the surface. For accelerogram A, the PGA is 0.16 g at 13 m depth and it increases to reach 0.26 g for the simulation with Vucetic and Dobry [17] and 0.32 g for the simulation with experimental data. For accelerogram B, the PGA is 0.18 g at 13 m depth and it increases to reach 0.19 g for the simulation with Vucetic and Dobry [17] and 0.27 g for the simulation with experimental data.

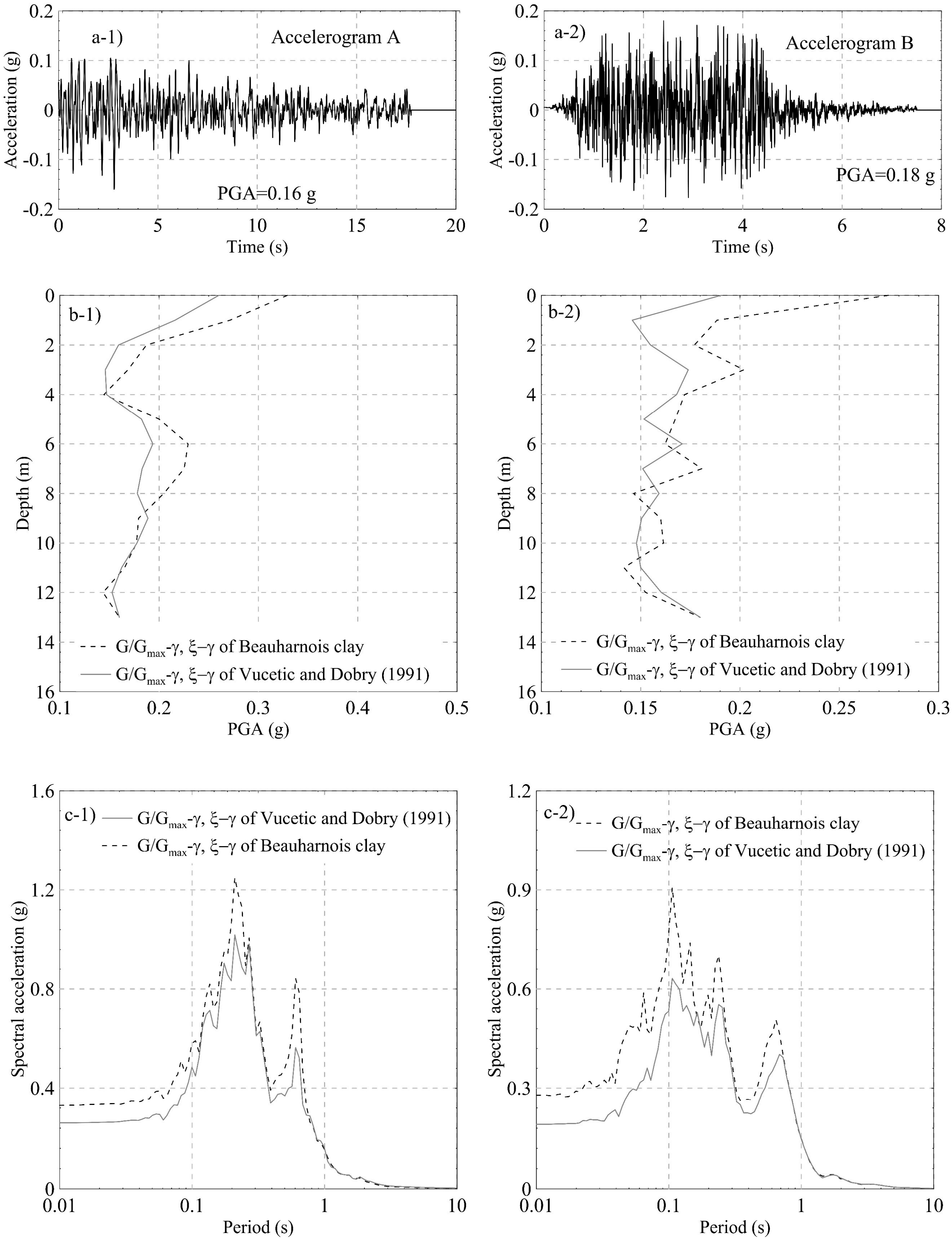

Figure 5: a) Applied accelerograms at the rock b) PGA profiles c) spectral accelerations at the surface

Except for some points, the profiles obtained using the experimental data show almost higher PGA than the profile obtained using Vucetic and Dobry [17] model. Figure 5c-1 and 5c-2 present the obtained spectral acceleration at the surface. For both accelerograms A and B, the spectral acceleration obtained using experimental data is higher than the spectral acceleration obtained using Vucetic and Dobry [17] model. These differences are more important for a period ranging from 0.01 s to about 0.8 s. These results indicate that the use of the real dynamic properties of eastern Canada clay may produce higher amplification of the ground motion than the use of the literature models.

CONCLUSION

The shear modulus reduction and damping curves of very sensitive Beauharnois clay were investigated in the laboratory by using the T_xSS apparatus. The maximum shear modulus was also determined and validated in the laboratory by means of the P-RAT measurements. The comparison with the literature models indicates that the obtained G/G_{max}-γ_c and ξ-γ_c curves exhibit different trend: G/G_{max} exhibit higher values and ξ exhibit lower values with respect to γ_c. The determined curves show also that beyond 0.2 % of γ_c, the damping ratio become approximately constant which is different from some literature results. Such behavior needs more investigations in order to determine its causes. A numerical simulation of soil column was carried out to investigate the effect of the difference between the curves on the dynamic response of the soil deposit. The results show that the application of the real G/G_{max}-γ_c and ξ-γ_c curves may lead to a higher spectral acceleration of the ground motion at the surface than the use of the standards literature models.

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REFERENCE

[1] Crawford, C. B. (1968). Quick clays of eastern Canada. Engineering Geology, 2(4), 239-265.

[2] Leroueil, S., Tavenas, F., & Bihan, J. P. L. (1983). Propriétés caractéristiques des argiles de l'est du Canada. Canadian Geotechnical Journal, 20(4), 681-705.

[3] CNBC (2010). Code National du Bâtiment du Canada. Ottawa, Ont., National research council of Canada

[4] Kramer, S. L. (1996). Geotechnical earthquake engineering. In prentice–Hall international series in civil engineering and engineering mechanics. Prentice-Hall, New Jersey.

[5] Lee, K. L. (1979). Cyclic strength of a sensitive clay of eastern Canada. Canadian Geotechnical Journal, 16(1), 163-176.

[6] Javed, K. (2002). Strength of sensitive clay under cyclic loading. Master thesis. Concordia University, Quebec, Canada.

[7] Rahhal, M. E. (1991). Propriétés dynamiques et réponse sismique des dépots argileux de l'Est du Canada. Master thesis. Université de Sherbrooke, Quebec, Canada.

[8] Chahde, J. 1987. Etude du comportement élastique et du problème K_O pour les argiles structurées de 1'Est du Canada. Thèse de doctorat, Département de génie civil, Université de Sherbrooke, Sherbrooke, Québec, Canada.

[9] Warde, J. (1989). Propriétés dynamiques de quelques sols cohésifs de l'Est du Canada. Master thesis. Université de Sherbrooke, Quebec, Canada.

[10] Chekired, M., Lemire, R., Karray, M., & Hussien, M. N. (2015). Experiment setup for simple shear tests in a triaxial cell: TxSS. In Proceedings of the 68th Conference of the Canadian Geotechnical Society, Quebec City. Paper (No. 365).

[11] ASTM International. (2011). ASTM D2435/D2435M-11 Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. American Society for Testing and Materials, West Conshohocken, Pa.

[12] Karray, M., Ben Romdhan, M., Hussien, M. N., & Éthier, Y. (2015). Measuring shear wave velocity of granular material using the piezoelectric ring-actuator technique (P-RAT). Canadian Geotechnical Journal, 52(9), 1302-1317.

[13] Ethier, Y. A. (2009). La mesure en laboratoire de la vitesse de propagation des ondes de cisaillement. Doctoral dissertation. Université de Sherbrooke, Quebec, Canada.

[14] ASTM International. (2011). ASTM D4767-11 Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils. American Society for Testing and Materials, West Conshohocken, Pa.

[15] Saada, A. S., Fries, G., & Ker, C. C. (1983). An evaluation of laboratory testing techniques in soil mechanics. Soils and foundations, 23(2), 98-112.

[16] Bjerrum, L., & Landva, A. (1966). Direct simple-shear tests on a Norwegian quick clay. Geotechnique, 16(1), 1-20.

[17] Vucetic, M., & Dobry, R. (1991). Effect of soil plasticity on cyclic response. Journal of geotechnical engineering, 117(1), 89-107.

[18] Darendeli, M. B. (2001). Development of a new family of normalized modulus reduction and material damping curves.

[19] Zhang, J., Andrus, R. D., & Juang, C. H. (2005). Normalized shear modulus and material damping ratio relationships. Journal of Geotechnical and Geoenvironmental Engineering, 131(4), 453-464.

[20] Okur, D. V., & Ansal, A. (2007). Stiffness degradation of natural fine-grained soils during cyclic loading. Soil Dynamics and Earthquake Engineering, 27(9), 843-854.

[21] Chehat, A., Hussien, M. N., Abdellaziz, M., Chekired MC, M., Harichane, Z., & Karray, M. (2018). Stiffness-and damping-strain curves of sensitive Champlain clays through experimental and analytical approaches. Canadian Geotechnical Journal.
[22] Lefebvre G. (2017) Sensitive Clays of Eastern Canada: From Geology to Slope Stability. In: Thakur V., L'Heureux JS., Locat A. (eds) Landslides in Sensitive Clays. Advances in Natural and Technological Hazards Research, vol 46. Springer, Cham
[23] Hashash, Y. M. A., Musgrove, M. I., Harmon, J. A., Groholski, D. R., Phillips, C. A., & Park, D. (2015). DEEPSOIL 6.1, user manual. Board of Trustees of University of Illinois at Urbana-Champaign, Urbana.
[24] Natural resources Canada (consulted 1 janvier 2019), website Natural ressources Canada, http://www.nrcan.gc.ca/
[25] Seed, H. B., Wong, R. T., Idriss, I. M., & Tokimatsu, K. (1986). Moduli and damping factors for dynamic analyses of cohesionless soils. Journal of geotechnical engineering, 112(11), 1016-1032.