SHEAR WAVE VELOCITY VALUES PREDICTED BY EMPIRICAL LABORATORY CORRELATIONS FOR EASTERN CANADIAN CLAYS

Dania ELBEGGO[1], Yannic ETHIER[2], Mourad KARRAY[3], Jean-Sébastien DUBÉ[2]

1. Ph.D. Candidate - Project Assistant at WSP and 2. Professor, Department of Construction Engineering, École de Technologie Supérieure, Montréal, Québec, Canada.
3. Professor, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Québec, Canada.

GeoCalgary 2022 October 2-5 Reflection on Resources

ABSTRACT
Shear wave velocity, V_s, is a mechanical geotechnical parameter required for assessing the dynamic response of a deposit. Existing V_s laboratory correlations are examined and grouped into different general forms based on geotechnical properties used to establish them. This paper presents V_s values calculated based on published correlations applied for saturated deposits of eastern Canadian clay and discuss the range of V_s values. This range is also examined for each general form of correlations, considering the physical properties of analyzed sites. The analysis shows an important variation range of V_{s1} values predicted by different forms of correlations and even by correlations which have the same general form. This variation range (ΔV_{s1}) raises questions about the applicability and accuracy of existing laboratory correlations. The analysis also emphasizes the need to establish correlations, more adapted for eastern Canadian clays, that will yield V_s values with a greater accuracy, in order to use this parameter for geotechnical characterization purposes.

RÉSUMÉ
La vitesse de propagation des ondes de cisaillement, V_s est un paramètre géotechnique mécanique permettant d'évaluer la réponse dynamique d'un site. Des corrélations existantes de V_s, établies en laboratoire sont examinées et regroupées sous différentes formes générales en se basant sur les propriétés géotechniques utilisées pour les établir. La plage de variation de V_s est déterminée pour différentes formes générales de corrélations, en tenant compte des propriétés physiques des dépôts saturés d'argile de l'est du Canada. L'analyse montre une variation importante entre des valeurs de V_{s1} prédites par différentes formes générales corrélations et même par les corrélations qui ont la même forme générale. La variation (ΔV_{s1}) soulève des questions sur l'applicabilité et la précision des corrélations existantes. L'analyse souligne également la nécessité d'établir des corrélations, plus adaptées pour l'argile de l'est du Canada, afin d'utiliser ce paramètre à des fins de caractérisation géotechnique.

1 INTRODUCTION

In response to the increasing awareness in seismic site characterization, research efforts are currently being oriented to assess the seismic response of a deposit. The shear wave velocity, V_s is a fundamental parameter involved in dynamic analysis of a soil deposit. This parameter is used to assess the liquefaction potential and to predict the behaviour of soils when subjected to seismic waves.

In addition to the above-mentioned usefulness, shear wave velocity can be considered as a mechanical geotechnical parameter relevant for characterizing the behaviour of soils under very small strain ($\gamma < 10^{-3}$%).

In a linear isotropic elastic medium, the shear wave velocity is related to the soil stiffness under small strain domain, or shear modulus, G_{max} by the relationship:

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

where ρ is the bulk density of the soil and V_s is the shear wave velocity, with consistent set of units.

Laboratory experiments on cohesive soils showed that the shear wave velocity, V_s depends on many geotechnical properties, including the vertical effective stress, void ratio and overconsolidation ratio. The influence of these geotechnical properties is well known and have been studied by Hardin and Black (1968), Hardin and Drnevich (1972).

The main purpose of this paper is to examine the expected range of V_s values calculated based on empirical laboratory correlations taken from the literature for eastern Canadian clay. The analysis also presents the interval of V_{s1} values predicted by different general form of correlations and then discuss the accuracy and applicability of these correlations for eastern Canadian deposits.

2 G_{MAX} OR V_S CORRELATIONS

Abundant number of empirical correlations have been proposed to estimate G_{max} or V_s based on geotechnical properties of clay. The correlations considered herein are grouped into different general forms. In the first form, G_{max} or V_s depend on three properties namely void ratio, e, mean effective stress, σ_m' and overconsolidation ratio, OCR as shown in Table 1. The first general form can be written as follows:

$$G_{max} = A\, F(e) \sigma_m'^{n}\, OCR^{K} \quad [2]$$

where F(e) is a function of the void ratio, n and K are exponents depending on the plasticity index of the soil, and A is a constant taking into account the influence of all other factors.

In the second form, presented in Table 1, the correlations depend also on the previous three soil properties (e, σ_m' and OCR). These correlations are expressed in terms of V_s according to equation 3:

$$V_s = F(e)\sigma_m'^{0.25}\,OCR^{K/2} \quad [3]$$

Laboratory tests on different clays have suggested that the influence of OCR may be neglected (Lo Presti and Jamiolkowski, 1998). Therefore, the form 3 correlations relate G_{max} to two parameters (e and σ_m'). These correlations are presented in Table 2 and the third general form can be written as follows:

$$G_{max} = A\,F(e)\sigma_m'^{n}\,P_a^{1-n} \quad [4]$$

where F(e) is a function of the void ratio equal to e^{-x}, P_a is the atmospheric pressure.

In other studies (Kagawa, 1992; Kallioglou et al. 2008), the constant A is replaced by a function of the plasticity index, F(PI):

$$G_{max} = F(e)\,F(PI)\,\sigma_m'^{n} \quad [5]$$

In other correlations, G_{max} or E_{max} does not take into account the effect of OCR. However, these correlations involve the vertical effective stress σ'_v, or the principal effective stresses (σ'_v, σ'_h) instead of σ'_m (Shibuya and Tanaka, 1996; Shibuya et al., 1997). The correlations are shown in Table 2 and their general forms are written as follows:

$$G_{max} = AF(e)\,(\sigma_v'\,\sigma_h')^{n} \quad [6]$$

$$G_{max}\,\text{or}\,E_{max} = A\,F(e)\,\sigma_v'^{n} \quad [7]$$

For the last general form, the influence of the e term is not considered and G_{max} or E_{max} depend on σ'_m and OCR only. The correlations are presented in Table 3 and take the general form:

$$G_{max}\,\text{or}\,E_{max} = A\sigma_m'^{n}OCR^{K} \quad [8]$$

Table 1. G_{max} or V_s correlations with OCR

Correlation	Geotechnical properties - Type of clay	Test Reference
$G_{max} = AF(e)\sigma_m'^{n}OCR^{K}$		
$G_{max\,(1)} = 1230\dfrac{(2.97-e)^2}{(1+e)}\sigma_m'^{0.5}OCR^{K}$	e:0.5-2, LL: 22-124, PI:2-85, Kaolinite and Boston blue clay	RC Hardin and Black (1969)
$G_{max\,(2)} = 1576\dfrac{(2.97-e)^2}{(1+e)}\sigma_m'^{0.5}OCR^{K}$	e:0.48-1.36, LL: 25-51, PI:12-30, OCR:1.8-6.8, Ontario clay	RC Kim and Novak (1981)
$G_{max\,(2)} = 90\dfrac{(7.32-e)^2}{(1+e)}\sigma_m'^{0.6}OCR^{K}$	e:1.5-4, LL: 65-110, PI:38-103, Teganuma clay	CT Kokusho et al. (1982)
$G_{max\,(2)1} = 4500\dfrac{(2.97-e)^2}{(1+e)}\sigma_m'^{0.5}OCR^{K}$	e:1.1-1.3, LL: 66, PI: 35, Kaolinite	RC Marcuson and Wahles (1972)
$G_{max\,(2)} = 9600\,(1/(1+1.2e^2))\sigma_m'^{0.5}OCR^{K}$	e:0.58-1.07, LL: 30-46, PI: 9-27, OCR: 1	RC Vrettos and Savidis (1999)
$G_{max\,(2)} = 1421\,e^{-1.504}\sigma_m'^{0.623}OCR^{K}$	e:0.37-1.36, LL: 21-99, PI:5-66, OCR: 1-2, Greece clay	RC Kallioglou et al (1999)
$G_{max\,(2)} = 466\dfrac{(3.40-e)^2}{(1+e)}\sigma_m'^{0.66}OCR^{K}$	e:0.68-1.4, LL: 38-70, PI:9-40, NC and OC clay	CT Okur and Ansal (2007)
$G_{max} = AF(e)\sigma_m'^{n}P_a^{1-n}OCR^{K}$		
$G_{max\,(2)} = 317(1/(0.3+0.7e^2))\sigma_m'^{0.56}P_a^{0.44}OCR^{K}$	e:1.38-2.31, LL: 63-122, PI: 36-79, CH	RC-TS Stokoe et al (1999)
$G_{max\,(2)} = 225\,\dfrac{(2.97-e)^2}{(1+e)}\sigma_m'^{0.55}P_a^{0.45}OCI$	W:24-29 %, LL: 30-38, PI:15-19, OCR: 1.1-1.7, Chicago clay	BE in T Kim and Finno (2014)
$V_s = F(e)OCR^{K/2}\sigma_m'^{n}$		
$V_s = (103.6 - 34.9e)\,OCR^{K/2}\sigma_m'^{1/4}$	e:0.5-2, LL: 22-124, PI:2-85, Kaolinite and Boston blue clay	RC Hardin and Black (1969)
$V_s = (39.3 - 56.44\log(e))\,OCR^{K/2}\sigma_m'^{1/4}$	e:0.48-1.36, LL: 25-51, PI:12-30, OCR:1.8-6.8, Ontario clay	RC Kim and Novak (1981)
$V_s = (66 - 123\log(e))\,OCR^{K/2}\sigma_m'^{1/4}$	e:0.38-2.28, LL: 25-96, PI:10-64, Kaolinite Bentonite	RC Anderson (1974)

(1) G_{max} in psi, (2) G_{max} in kPa, V_s in m/s, K = F(PI), PI: plasticity index, RC: Resonant Column, CT: Cyclic Triaxial, TS: Torsional Shear, BE: Bender Element.

Table 2. E_{max} or G_{max} correlations without OCR

Correlation	Geotechnical properties - Type of clay	Test Reference
$G_{max} = F(e)\,F(PI)\,\sigma'^{n}_{m}$		
$G_{max} = \dfrac{358 - 3{,}8\,PI}{0{,}4 + 0{,}7e}\,\sigma'_m$	e: 0.7-2.31, LL:50-95, PI:25-52, OCR: 1, Soft marine clay	RC Kagawa (1992)
$G_{max1} = (5660 - 80\,PI)\,e^{-0.63}\sigma'^{0.5}_{m}$	e: 0.55-1.525, LL:32-70, PI:10-43, Reconstituted samples (CL-CH)	RC Kallioglou et al (2008)
$G_{max2} = (6290 - 80\,PI)\,e^{-0.63}\sigma'^{0.5}_{m}$	e: 0.4-0.71, LL:21-58, PI:5-37, Undisturbed samples (CL-CH)	
$G_{max} = AF(e)\sigma'^{n}_{m}P_a^{1-n}$		
$G_{max1} = 506\,e^{-1.1}\sigma'^{0.42}_{m}p_a^{0.58}$	e:0.49-0.6, LL: 40-46, PI:24-30, OCR: 3, Clayey silts, Benevento clay	RC-BE D'Elia and Lanzo (1996)
$G_{max2} = 410\,e^{-1.2}\sigma'^{0.59}_{m}p_a^{0.41}$	e:0.77-1.03, LL: 37-58, PI:23-38, OCR: 1, Clayey silts, Garigliano clay	
$G_{max} = 740\,e^{-1.27}\sigma'^{0.46}_{m}p_a^{0.54}$	e:1-1.8, LL: 30-57, PI:10-30, OCR: 2.8-8.8, Avezzano clay	RC Lo Presti and Jamiolkowski (1998)
$G_{max} = 440\,e^{-1.11}\sigma'^{0.58}_{m}p_a^{0.42}$	e:0.9-1.2, LL: 25-60, PI:10-40, OCR: 1.2-1.4, Garigliano clay	
$G_{max} = 500\,e^{-1.33}\sigma'^{0.4}_{m}p_a^{0.6}$	e:0.6-0.8, LL: 30-57, PI:15-40, OCR: 1.8-2.5, Montalado di Castro clay	
$G_{max} = 520\,e^{-1.30}\sigma'^{0.5}_{m}p_a^{0.5}$	e:1.4-1.8, LL: 71, PI:44, OCR: 1-1.1, Panigaglia clay	
$G_{max} = 640\,e^{-1.52}\sigma'^{0.4}_{m}p_a^{0.6}$	e:1.6-3, LL: 90-120, PI:45-75, OCR: 1.1-1.8, Fucino clay	
$G_{max} = 500\,e^{-1.43}\sigma'^{0.44}_{m}p_a^{0.56}$	e:0.8-1.8, LL: 33-77, PI:23-46, OCR: 1.5-2, Pisa clay	
$G_{max}\,ou\,E_{max} = AF(e)\sigma'^{n}_{v}\sigma_r^{1-n}$		
$G_{max} = 5000\,e^{-1.5}\sigma'^{0.5}_{v}\sigma_r^{0.5}$	PI:19-152, OCR: 1-2.6, Holocence deposits clay	BE Shibuya and Tanaka (1996)
$G_{max} = 24000\,(1 + e)^{-2.4}\sigma'^{0.5}_{v}\sigma_r^{0.5}$	LL: 41-120, PI:19-59, Reconstituted clay samples	BE Shibuya et al. (1997)
$E_{max\,(1)} = 273\,e^{-2.44}\sigma'^{0.44}_{v}$	LL: 46, PI:30, OCR: 1-8, e: 0.8-1.1, Boston clay	T Santagata et al. (2005)

(1) E_{max} in MPa (ν=0.5), G_{max} in kPa, RC: Resonant Column, BE: Bender Element, T: Undrained Triaxial Compression, Pa: atmospheric pressure (kPa), $\sigma_r = 1\text{kPa}$

It is important to note that these correlations have been established for a given soil and a given range of geotechnical properties. More details about these correlations are presented in the references listed in tables 1, 2, and 3.

Table 3. E_{max} or G_{max} correlations without void ratio

Correlation	Geotechnical properties, Type of clay	Test Reference
$G_{max} = A\,\sigma'^{n}_{m}\,P_r^{1-n}OCR^K$		
$\dfrac{G_{max\,(3)}}{P_r} = A\,(\dfrac{P'}{P_r})^n\,R_0^m$	PI:10-44, OCR:1-8, Kaolinite clay	BE in TC Viggiani and Atkinson (1995)
$G_{max}\ or\ E_{max} = A\,\sigma'^{n}_{m}OCR^K$		
$G_{max\,(1)} = 375\sigma'^{0.85}_{m}OCR^{0.59}$	LL:34-35, PI:14-15, Gulf of Alaska clay	RC Singh and Gardner (1979)
$G_{max(1)} = 440\sigma'^{0.84}_{m}OCR^{0.27}$	LL:32-39, PI:16-22, OCR:5-9, Clay of AGS CL	RC-CT Koutsoftas and Fischer (1980)
$G_{max\,(1)} = 125\sigma'^{1.18}_{m}OCR^{0.69}$	LL:63-64, PI:32-38, OCR:5-9, Clay of AGS CH	
$G_{max\,(1)} = 165\sigma'^{0.95}_{m}OCR^{0.51}$	LL:88, PI:43, San Francisco Bay Mud clay	RC Isenhower (1979), Lodde (1980)
$E_{max\,(2)} = 617\sigma'^{0.8}_{m}OCR^{0.15}$	LL:46, PI:23, OCR:1-8, e: 0.8-1.1, Boston clay	T Santagata et al. (2005)

(1) G_{max} in TSF, (2) E_{max} in MPa (ν=0.5), (3) G_{max} in kPa, R_0: overconsolidated ratio in terms of mean effective stress, P': mean effective stress (kPa), n, m and A are constants depending on plasticity index, P_r: reference pressure (taken as 1kPa), PI: plasticity index LL: liquid limit, RC: Resonant Column, CT: Cyclic Triaxial, T: Undrained Triaxial Compression.

3 ANALYZED SITES

The present analysis was performed with data from eight deposits of eastern Canadian clay namely: Saint-Alban (SA), Mascouche (M), Louiseville (L), Berthierville (B), Ottawa SP(O(SP)), Gloucester (G), Saint-Marcel (SM) and Varennes (V). Table 4 presents the main geotechnical properties of these investigated sites. As shown from this table, the sites have a void ratio varying between 1.5 and 2.2 and an overconsolidation ratio varying between 1.1 and 5.9. The sites are characterized by a liquid limit ranging between 35 and 66 and a plasticity index varying between 15 and 43. Therefore, the soils considered in this study are classified as CL (low-plasticity clay) or CH (high-plasticity clay) according to the Unified Soil Classification System (USCS). More details on these sites are available in the references listed in Table 4.

For four of these sites, in situ V_s measurements were obtained using different techniques: the Cross-Hole method was used to determine V_s for the Louiseville, Mascouche and Berthierville sites (Bourgeois, 1997). For St-Alban site, V_s was determined by the Spectral analysis of surface wave (SASW) with higher Rayleigh mode separation (Karray, 1999). These V_s values are also presented in Table 4.

Table 4. Characteristics of analyzed sites

Site Sample/ Depth (m)	e	LL	PI	OCR	$V_{s\ in\ situ}$	Reference
St-Alban SA/6	1.7	40	17	2.4	82.3*	Lefebvre et al. (1994), Tavenas et al. (1975)
Louiseville L/9.5	2.1	65	43	2.7	127_{CH}	Hamouche et al.
Berthierville B/4.6	1.5	35	15	1.1	99_{CH}	(1995) Bourgeois
Mascouche M/7.7	1.9	60	32	5.9	158_{CH}	(1997)
Ottawa O(SP)/8.8	1.8	65	37	4.8		
Varennes V/7.1	1.8	66	41	3.1		Philibert (1984)
Gloucester G/3.8	2.2	55	30	1.8		
St-Marcel SM/5.3	2.2	60	35	2.3		

CH: Cross-hole, *: V_s obtained from Spectral Analysis of Surface Wave (SASW) with Rayleigh mode separation (Karray, 1999).

4 METHOD AND ANALYSIS

The correlations described in section 2 and listed in Tables 1, 2 and 3 were used to estimate V_s values for the eight deposits of eastern Canadian clay selected from literature and presented in Table 4. The correlations were applied taking into account the limited range of plasticity index for which they were established as they appear in the different publications.

For correlations written in terms of G_{max}, equation [1] was used to obtain V_s values. For correlations in terms of E_{max}, G_{max} was first calculated using the equation $G_{max}=E_{max}/(1+2\upsilon)$, considering the Poisson's ratio υ is 0.5 and then equation [1] was used to calculate V_s values.

The V_s values obtained according to different general forms of empirical correlations are normalised by using σ'_v or σ'_m, depending on the stress terms considered in the selected correlation. Therefore, a normalized shear wave velocity, V_{s1} can be determined using the following expression:

$$V_{S1} = V_s \left(\frac{P_a}{\sigma'_{v,m}}\right)^{0.25} \qquad [9]$$

where V_{s1} is the normalized shear wave velocity in m/s, P_a is the reference stress typically 100 kPa.

The application of correlations to the sites under study helped assess the variation range of V_{s1} values for eastern Canadian clays. For each site, the V_{s1Min} and V_{s1Max} obtained according to different correlations have been identified and are plotted in Figure 1. As stated from this figure, an important scatter between V_{s1Min} and V_{s1Max} values is noticed for studied sites. The ΔV_{s1Min} and ΔV_{s1Max} are obtained for Louisville (L) and Gloucester (G) sites respectively; these values are 57 m/s and 101 m/s as shown in Figure 1.

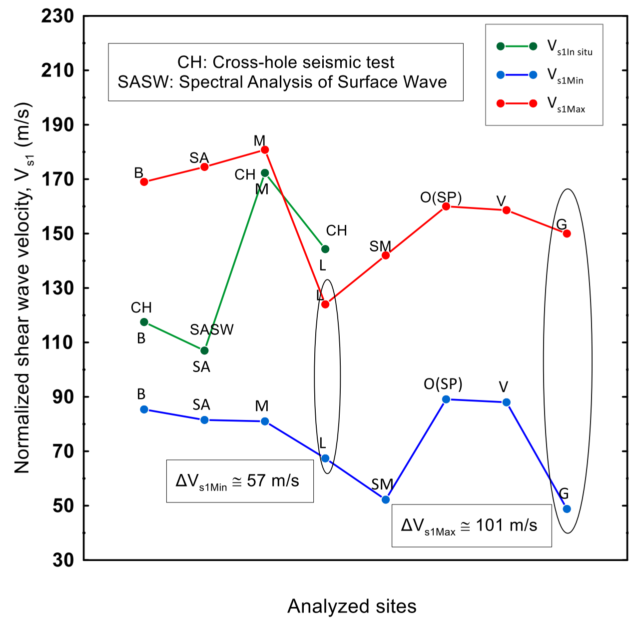


Figure 1. $V_{s1In\ situ}$ values and those predicted by empirical correlations

The existing correlations may appear useful for estimating V_s for preliminary feasibility study or site investigation when in situ V_s measurements are not readily available. Thus, it is helpful to compare the V_{s1} values estimated based on empirical correlations with those measured in situ using Cross-hole and SASW methods. The results are also presented in Figure 1. This figure shows that the $V_{s1In\text{-}situ}$ value is greater than V_{s1Max} for Louiseville site. However, the $V_{s1In\text{-}situ}$ of Mascouche site (M) is fairly closed to $V_{s1(max)}$. The $V_{s1In\text{-}situ}$ values of Berthierville (B) and Saint-Alban (SA) sites are well located between V_{s1Min} and V_{s1Max}. Indeed, no tendency is noticed when in situ V_{s1} values are compared to those predicted by empirical laboratory correlations (Fig.1).

The discrepancy in results presented in Figure 1 raises questions about the applicability of published correlations for eastern Canadian clays. The analysis also emphasizes the need for a greater accuracy in V_s estimated from correlations in order to use this parameter for geotechnical characterization purposes. Several studies (Cai et al. 2010; Clayton 2011; Duan et al. 2019) reported that the accuracy of laboratory results is strongly affected by the sample disturbance (sampling and stress relief) and high-quality undisturbed samples are required in order to improve the ability of laboratory tests to reproduce the initial in situ conditions. Also, the published correlations considered herein have been established based on laboratory tests performed using piezoelectric transducers and numerous researchers raise difficulties in the interpretation of bender elements results such as near field effect, interference of waves at the boundaries, mixed radiation of both primary (P) and shear waves and uncertain detection of first arrival time of the shear wave (Arulnathan et al. 1998; Lee and Santamarina 2005).These difficulties influence on the signals interpretation process and therefore on the results of bender elements test.

4.1 Range of V_{s1} according to PI

For investigated sites considered in this analysis, the expected range of V_{s1} values was calculated based on published correlations according to the plasticity index. Figures 2 and 3 present V_{s1} values predicted by different general forms of correlations as a function of PI. As stated in these figures, the V_{s1} values increase with decreasing PI of investigated sites. The lower and upper bounds of V_{s1} interval are plotted in Figs 2 and 3 for each general form of correlations. These bounds illustrate the variation between maximum and minimum normalized shear wave velocities ($\Delta V_{s1}=V_{s1Max}-V_{s1Min}$) obtained for plasticity index range from 15 to 43.

It can be mentioned from Figs 2 and 3, the variation range, ΔV_{s1} calculated for each general form of correlation varies between 31 and 63 m/s. Also, the correlations written in terms of V_s and including the geotechnical properties, e, σ'_m and OCR present the highest ΔV_{s1} (63 m/s, Fig. 2b). This high dispersion between V_{s1} values predicted by these correlations for low and high plasticity clay can be attributed to different void ratio function F(e) included in these correlations (Fig.2b). However, the ΔV_{s1} values of other general forms of correlations are close to each other (Figs. 2a, 2c, 3a, 3b and 3c).

4.2 Range of V_{s1} according to e_0

A significant variation between the upper and lower bounds of V_{s1} (ΔV_{s1} = 31 to 63 m/s) is observed with the application of published correlations according to PI. This variation is mainly due to the different void ratio functions included in these correlations (Tables 1 and 2). Indeed, it is important to examine the variation range of V_{s1} with respect to void ratio values of investigated sites for correlations considering void ratio function and listed in Tables 1 and 2.

Figures 4 and 5 present V_{s1} values predicted by different general forms of correlations according to void ratio values of selected sites. As illustrated in Figs. 4 and 5, V_{s1} values increase with decreasing void ratio values. For each general form of correlations, the lower and upper bounds of V_{s1} range are identified and plotted in Figs. 4 and 5. This V_{s1} interval indicates the variation between V_{s1Max} and V_{s1Min} predicted by different general forms of correlations. As illustrated in Figs. 4 and 5, ΔV_{s1} values are between 20 and 50 m/s for the 1.3 to 2.2 void ratio range.

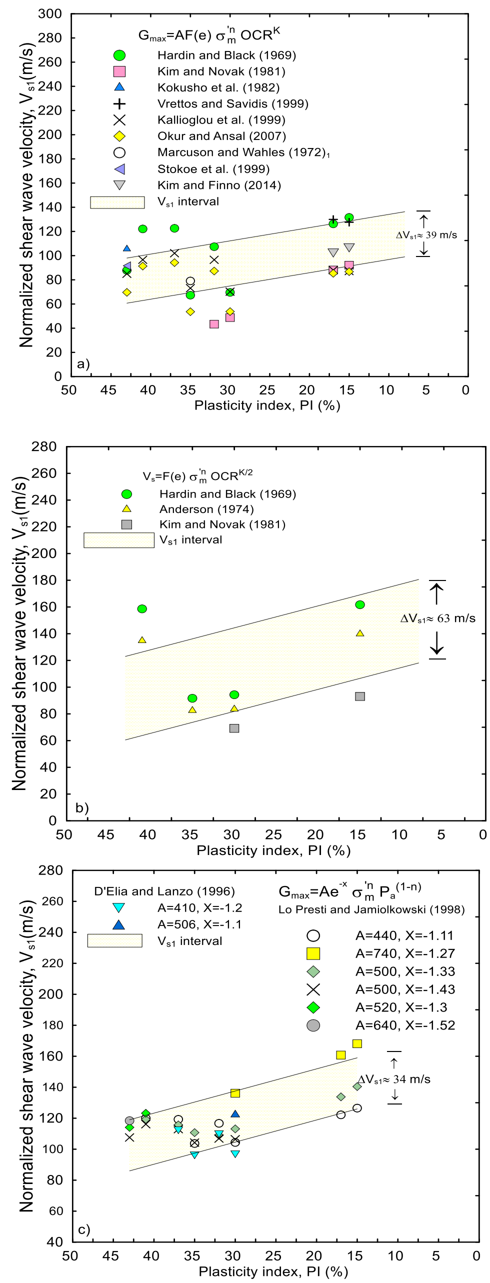


Figure. 2: V_{s1}-PI values predicted by different general forms of empirical correlations: a) $G_{max}=AF(e)\sigma'^{n}_{m}OCR^{K}$; b) $V_s=F(e)OCR^{K/2}\sigma'^{n}_{m}$; c) $G_{max}=AF(e)\sigma'^{n}_{m}P_a^{1-n}$

It can be noted here that the correlations of general form $G_{max}=F(e)\,F(PI)\,\sigma'^{n}_{m}$ present the highest value of variation (*ΔV_{s1}*= 50 m/s, Fig. 5a). This variation may be attributed not only from the void ratio functions, F(e), but is also a result of the plasticity index functions, F(PI) included in these correlations. On the other hand, a lowest *ΔV_{s1}* (20 m/s, Fig. 5b) is observed for correlations of *G_{max}* or *E_{max}* written in terms of void ratio and vertical effective stress.

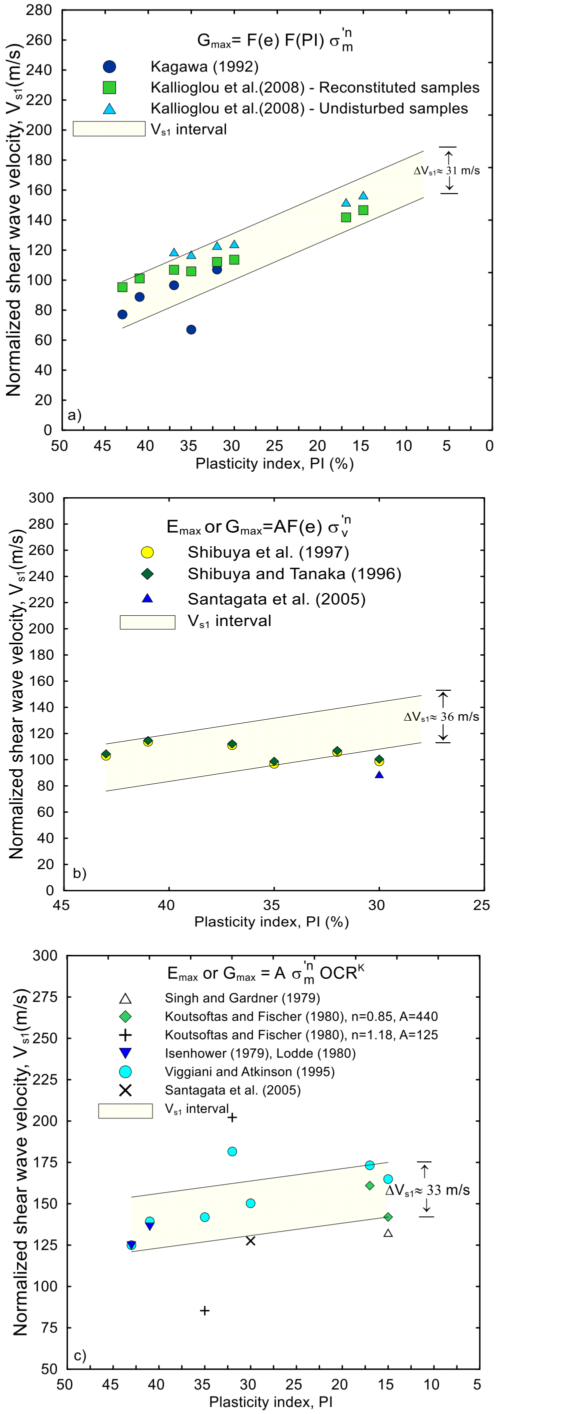


Figure. 3: V_{s1}-PI values predicted by different general forms of empirical correlations: a) $G_{max} = F(e)\,F(PI)\sigma'^n_m$; b) E_{max} or $G_{max} = AF(e)\sigma'^n_v$; c) G_{max} or $E_{max} = A\sigma'^n_m OCR^K$

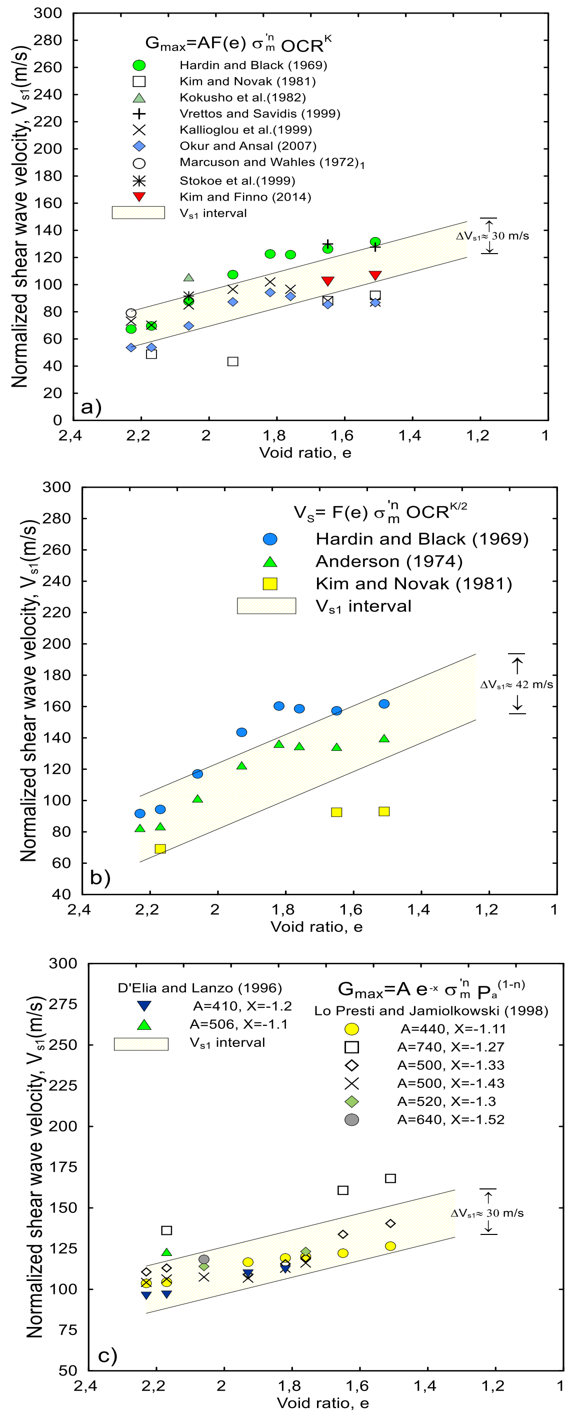
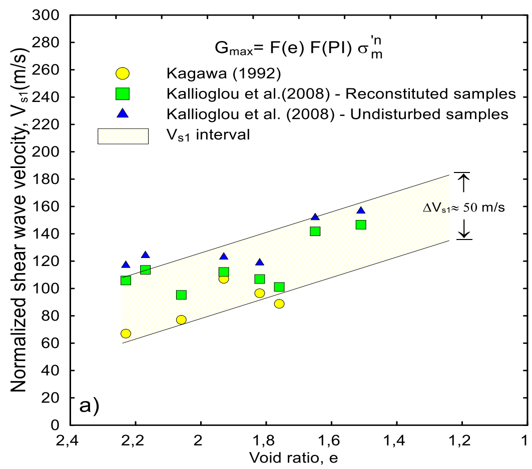


Figure. 4: V_{s1}-e values predicted by different general forms of empirical correlations: a) $G_{max} = AF(e)\sigma'^n_m OCR^K$; b) $V_s = F(e)OCR^{K/2}\sigma'^n_m$; c) $G_{max} = AF(e)\sigma'^n_m P_a^{1-n}$

The analysis showed an important variation range, ΔV_{s1} between V_{s1} values predicted by different general forms of correlations (≈ 57-100 m/s) and even by correlations having the same general form (≈ 20-60 m/s). An error exceeding 100 m/s in estimating V_{s1} is likely enough to prevent the use of this parameter for geotechnical engineering needs. Therefore, it is difficult to predict V_s from existing published correlation for eastern Canadian clays.



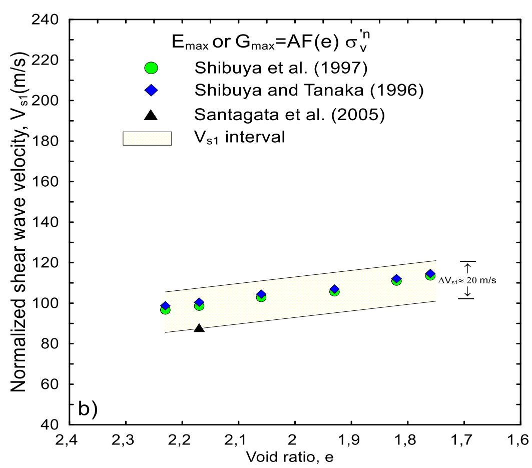


Figure. 5: V_{s1}-e values predicted by different general forms of empirical correlations: a) $G_{max} = F(e)\,F(PI)\sigma'^{n}_{m}$; b) E_{max} or $G_{max} = AF(e)\sigma'^{n}_{v}$

5 SUMMARY AND CONCLUSION

The following conclusions were drawn from the previous analysis, considering eight sites of eastern Canadian clays:

1. There is an important variation range between V_{s1Max} and V_{s1Min} calculated based on existing correlations when applied to eastern Canadian deposits.
2. The accuracy of V_{s1} values derived from empirical laboratory correlations appears strongly influenced by the effects of sample disturbance (sampling and stress relief). Therefore, high-quality undisturbed samples are required to perform laboratory tests.
3. The variation range ($\Delta V_{s1}=V_{s1Max}-V_{s1Min}$) calculated for each general forms of correlations examined herein according to plasticity index and void ratio values of selected sites is mainly affected by the void ratio functions embedded in these correlations.
4. The application of existing laboratory correlations to selected sites indicate a significant scatter between V_{s1Max} and V_{s1Min} (≈ 57-100 m/s) predicted by different forms of correlations and even by correlations which have the same general form (≈ 20-60 m/s). Therefore, it is difficult to predict shear wave velocity from existing correlations examined in this paper for eastern Canadian clays and it is important to establish new correlations more adapted for eastern Canadian clays based on reliable laboratory measurements of shear wave velocity.

REFERENCES

Anderson, D. J. 1974. Dynamic Modulus of Cohesive Soils, PhD Thesis, University of Michigan, U.S, 311 p.

Arulnathan, R., Boulanger, R. W., and Riemer, M. F. 1998. Analysis of Bender Element tests, Geotechnical Testing Journal, ASTM, 21(2), 120–131.

Bourgeois, C. 1997. Module de cisaillement à petites déformations des argiles de Champlain, Master, Université de Laval, Canada, 130 p.

Cai, G. J., Liu, S.Y., and Tong, L.Y. 2010. Field evaluation of deformation characteristics of a lacustrine clay deposit using seismic piezocone tests. Engineering Geology, 116(3):251-260.

Clayton, C.R.I. 2011. Stiffness at small strain: research and practice, Géotechnique, 61(1): 5-37.

D' Elia, B., and Lanzo, G. 1996. Laboratory and field determinations of small-strain shear modulus of natural soil deposits, Proceedings of the 11th World Conference on Earthquake Engineering.

Duan, W., Cai, G., Liu. S., and Puppala. A. 2019. Correlations between shear wave velocity and geotechnical parameters for Jiangsu clays of China. Pure and Applied Geophysics, 176(2): 669-684.

Hamouche, K.K, Leroueil, S, Roy, M and Lutenegger A.J.1995. In Situ Evaluation of K_0 in Eastern Canada Clays, *Canadian geotechnical journal*, 32: 677-688.

Hardin, B.O and Black, W.L. 1968. Vibration Modulus of Normally Consolidated Clay, *Journal of the Soil Mechanics and Foundations* Division, 94(SM2): 353-373.

Hardin, B.O., Black, W.L. 1969. Vibration Modulus of Normally Consolidated Clay closure, ASCE *Journal of the Soil Mechanics and Foundations* Division, 95(SM6): 1531-1537.

Hardin, B O., and Drnevich, V. P. 1972. Shear modulus and damping in soils: Design equations and curves, Journal of the Soil Mechanics and Foundations Division, 98(SM7): 667-693.

Isenhower, W.M. 1979. Torsional Simple Shear/Resonant Column Properties of San Francisco Bay Mud, PhD thesis GT80-1, University of Texas, Austin.

Kagawa, T.1992. Moduli and damping factors of soft marine clays, *Journal of Geotechnical Engineering*, 118(9): 1360-1375.

Kallioglou, P., Tika, T., and Pitilakis, K. 1999. Dynamic characteristics of natural cohesive soils, proceeding of the second international conference on earthquake geotechnical engineering, Balkema, Rotterdam, 113-117.

Kallioglou, P., Tika, T., and Pitilakis, K. 2008. Shear modulus and damping ratio of cohesive soils, *Journal of Earthquake Engineering*, 12(6): 879-913

Karray, M. 1999. Utilisation de l'analyse modale des ondes de Rayleigh comme outil d'investigation géotechnique in-situ, Ph.D. Thesis, Department of civil engineering, University of Sherbrooke, Canada, 291 p.

Kim, T.C and Novak, M. 1981. Dynamic Properties of some Cohesive Soils of Ontario, *Canadian Geotechnical Journal*, 18: 371-389.

Kim, T and Finno, R.J. 2014. Elastic shear modulus of compressible Chicago clay, *Journal of Civil Engineering*, 18(7): 1996-2006.

Koutsoftas, D.C and Fischer, J.AC. 1980. Stress History Effects on the Dynamic Properties of two Marine Clays, ASCE *Journal of Geotechnical Engineering* division, 106(GT6): 645-657.

Kokusho, T, Yoshida, Y and Esashi, Y. 1982. Dynamic Properties of Soft Clay for Wide Strain Range, *Journal of soils and foundations*, 22(4): 1-18.

Lefebvre, G, Leboeuf, D, Rahhal, M.E, Lacroix, A. and Warde, J. 1994. Laboratory and Field Determinations of Small Strain Shear Modulus for Structured ChampIain Clay, *Canadian Geotechnical Journal*, 31: 61-70.

Lee, J. S., and Santamarina, J. C. 2005. Bender Elements: performance and signal interpretation, Journal of Geotechnical and Geoenvironmental Engineering, 131(9): 1063-1070.

Lodde.P.F.1980. Dynamic Response of San Francisco Bay Mud, PhD thesis GT80-2, University of Texas, Austin.

Lo Presti, D.C.F. and Jamiolkowski, M. 1998. Discussion: Estimate of Elastic Shear Modulus in Holocene Soil deposits, *Journal of Soils and Foundations*, 38: 263-265.

Marcuson, W.F and Wahls, H.E. 1972. Time Effects on Dynamic Shear Modulus of Clays, *Journal of Soil Mechanics and Foundation,* 98(SM12): 1359-1373.

Okur, D.V., and Ansal, A. 2007. Stiffness degradation of natural fine-grained soils during cyclic loading, *Journal of Soil Dynamics and Earthquake Engineering*, 27: 843-854.

Philibert, A. 1984. Le champ des contraintes et son évolution sous des conditions de chargement unidimensionnel dans les dépôts d'argile structurée de l'est du Canada, Ph.D. Thesis, Department of civil engineering, Université de Sherbrooke: 495 p.

Santagata, M, Germaine, J.T and Ladd, C.C. 2005. Factors Affecting the Initial Stiffness of Cohesive Soil, *Journal Geotechnical and Geoenvironmental Engineering*, 131(4): 430-442.

Shibuya, S., and Tanaka, H.1996. Estimate of elastic shear modulus in Holocene soil deposits, Journal of Soils and Foundation, 36(4): 45-55.

Shibuya, S., Hwang, S.C., and Mitachi, T. 1997. Elastic shear modulus of soft clays from shear wave velocity measurement, Journal of Géotechnique, 47(3): 207-215.

Singh, R.D and Gardner, W.S 1979. Characterization of Dynamic Properties of Gulf of Alaska clays, Proceeding *ASCE Session on soil dynamics in the Marine Environment*, Boston, 24 p.

Stokoe, K.H.I., Darendeli, M.B., Andrus, R.D., and Brown, L.T. 1999. Dynamic soil properties: laboratory, field, and correlation studies, Proceedings of 2nd International Conference on Earthquake Geotechnical Engineering, Lisbon, Portugal, 811-845.

Tavenas, F. A., Blanchette, G., Leroueil, S., Roy.M. and La Rochelle, P. 1975. Difficulties in the In Situ Determination of K0 in Soft Sensitive Clays, *Proceeding of Conference: In Situ Measurement of Soil Properties,* 1: 450-476.

Viggiani, G and Atkinson, J.H. 1995. Stiffness of Fine-Grained Soils at Very Small Strains, *Journal of Géotechnique*, 45(2): 249-265.

Vrettos, C., and Savidis, S. 1999. Shear modulus and damping for Mediterranean Sea clays of medium plasticity, Proceeding of the second International Conference on Earthquake Geotechnical Engineering, Balkema, Rotterdam, 71–76.