Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

Shear wave velocity – SCPTU correlations for sensitive marine clays

M. Long
School of Civil Engineering, University College Dublin (UCD), Ireland

J.-S. L'Heureux
Norwegian Geotechnical Institute (NGI), Trondheim, Norway

ABSTRACT: The purpose of this paper is to encourage the use of the seismic cone penetrometer (SCPTU) in soil characterisation studies. There has been an increase in use of shear wave velocity (V_s) data in geotechnical engineering. This has been prompted by improvements in measurement and analytical systems. A significant advantage, as is confirmed here, is that V_s can be measured easily and repeatedly by several different techniques in the sensitive marine clays under consideration here. Here the focus is on the derivation of preconsolidation stress (p_c') from V_s. A rational method of determining a V_s/p_c' relationship is outlined with resorting to empirical data analysis. The proposed relationship is shown to work well for Canadian sensitive clay data as has been shown previously for Norwegian and Swedish clays

1 INTRODUCTION

There has been increasing recent use of shear wave velocity (V_S) measurements in geotechnical engineering practice. This has been driven by advances in cost effective and efficient methods of determination of V_s. Traditionally V_s measurements were used for seismic and dynamic analyses. However, they are being increasingly used for site characterisation studies, determination of soil parameters, foundation settlement analyses, assessment of sample disturbance and in the quality control of ground improvement schemes.

This paper focuses on the use of V_s values to provide first order estimates and quality control checking of some geotechnical properties of sensitive marine clays. Unfortunately, it has been shown that different forms of the correlation equations have been developed in different areas. It appears that local correlations are necessary for satisfactory use of the technique as demonstrated for example by L'Heureux and Long (2017), Duan et al. (2019) or Elbeggo et al. (2021). In this paper data for clays in eastern Canada will be examined and compared with similar clays in Norway and southern Sweden. The marine clays of these three countries have similar properties and share a comparable geological depositional environment.

The V_s profiles and basic soil properties in these areas will be studied to investigate any systematic differences and links between the V_s measurements. Focus will be then placed on use of V_s to determine the important preconsolidation stress (p_c') parameter. It is hoped that that this work can lead to a unification of these important practical relationships.

2 V_S MEASUREMENTS

2.1 *Invasive methods*

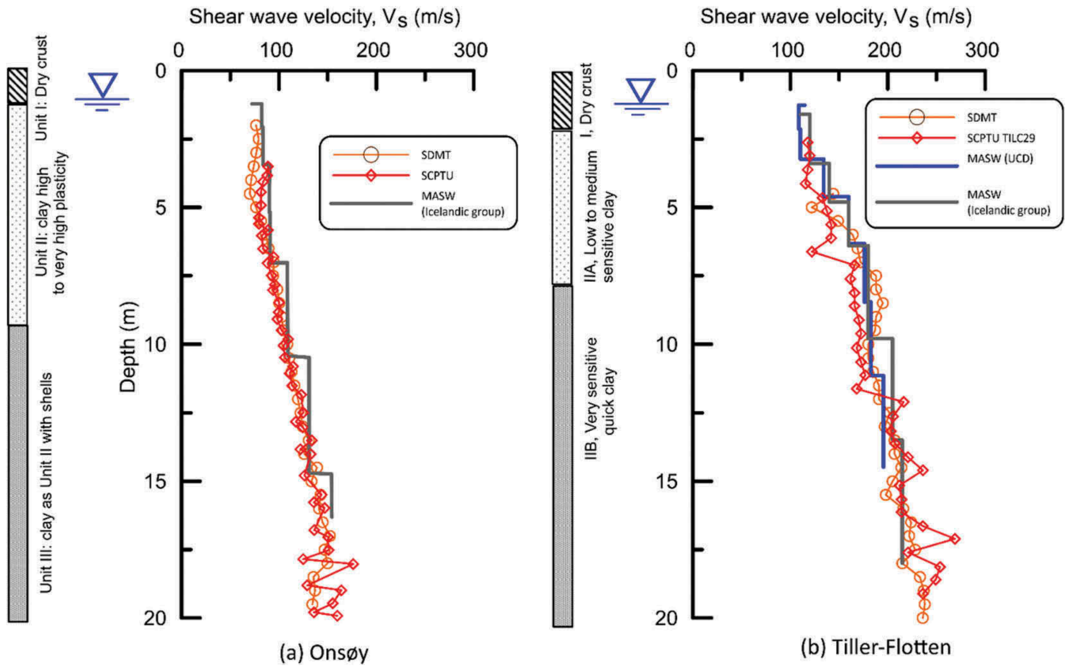
Geophysical methods can be divided into two categories: invasive and non-invasive. Common invasive methods include down-hole logging, cross-hole logging, suspension logging, seismic dilatometer (SDMT) and the seismic cone penetration test (SCPTU). In Scandinavia and Canada most invasive testing is done with the SCPTU.

A standard CPT is equipped with one or more seismic sensors. The seismic signals are only recorded during pauses in penetration, commonly every 0.5 or 1.0 m. A horizontal beam coupled to the ground surface by the weight of the testing vehicle is the source of the seismic energy. The beam is struck on end with a hammer to generate shear waves. V_s is determined from the travel-time differences along the assumed travel path length for receiver depth.

2.2 *Non-invasive methods*

Of available non-invasive geophysical methods, perhaps that most widely used in Scandinavia and Canada is the multichannel analysis of surface waves (MASW) technique. This technique was introduced in the late 1990s by the Kansas Geological Survey (Park et al., 1999). This method utilises the dispersion property of surface waves for the purpose of V_s profiling. Some further details on the use and validation of the MASW technique in Norwegian clays can be found in L'Heureux and Long (2017).

DOI: 10.1201/9781003308829-73



(a) Onsøy

(b) Tiller-Flotten

Figure 1. (a) V_s profiles Onsøy site. Data from Gundersen et al. (2019) and Icelandic group MASW from Ólafsdóttir et al. (2019) and (b) Tiller-Flotten. SDMT and SCPTU No TILC29 data from L'Heureux et al. (2019) and MASW from Icelandic Group from Ólafsdóttir et al. (2019).

2.3 *Comparison of V_s measurements using different techniques*

Between 2016 and 2019, NGI and its partners established five National GeoTest Sites (NGTS) in Norway for testing and verifying innovative soil investigation methods and foundation solutions (L'Heureux et al., 2017). Two of the sites at Onsøy and Tiller-Flotten are underlain by soft sensitive marine clays. The soils at Tiller-Flotten can be classified as quick below a depth of about 8 m using laboratory Swedish fall cone data. V_s profiles have been made with several techniques at these two sites, see Figures 1a and 1b.

The profiles from SCPTU, SDMT and MASW at the two sites are very similar. The V_s values at Onsøy are significantly less than those at Tiller-Flotten. The reasons for this will be explored below.

3 V_S PROFILES FROM NORWAY, SOUTHERN SWEDEN AND EASTERN CANADA

Several V_s profiles from a series of selected sites in Norway are shown on Figure 2a. The sites are from several areas of the country including southern Norway, the area around Trondheim and northern Norway. Measurements were made using a variety of techniques as discussed above. In general the V_s profiles are very similar and show V_s increasing approximately linearly with depth from about 125 m/s at the surface to about 225 m/s at 20 m depth. The Tiller-Flotten data falls within this general trend. An exception to the trend is the data from Onsøy where the values of V_s are significantly lower though they do show a clear tendency for an increase with depth.

A similar set of data from Southern Sweden is shown on Figure 2b. Again all values are very similar but here they are much lower than the Norwegian measurements with V_s increasing from some 50 m/s near ground level to 125 m/s at 20 m depth. In fact the Swedish data is very similar to the Onsøy profile.

A compilation of available Eastern Canadian data is shown on Figure 3. Many of the profiles fall within the bounds of the Southern Sweden sites. An exception is the profile from the Quyon Landslide site and perhaps the City of Ottawa data.

4 COMPARISON OF PROPERTIES OF CLAYS FROM THE THREE COUNTRIES

A summary of the key properties of the clays from the three countries is given on Table 1. For this purpose typical sites have been chosen, namely Göteborg Central Station from Southern Sweden, St. Alban from Eastern Canada as well as the two NGTS sites at Onsøy and Tiller-Flotten from Norway.

The Tiller-Flotten site (and generally many of the Norwegian sites) are significantly different from the other sites.

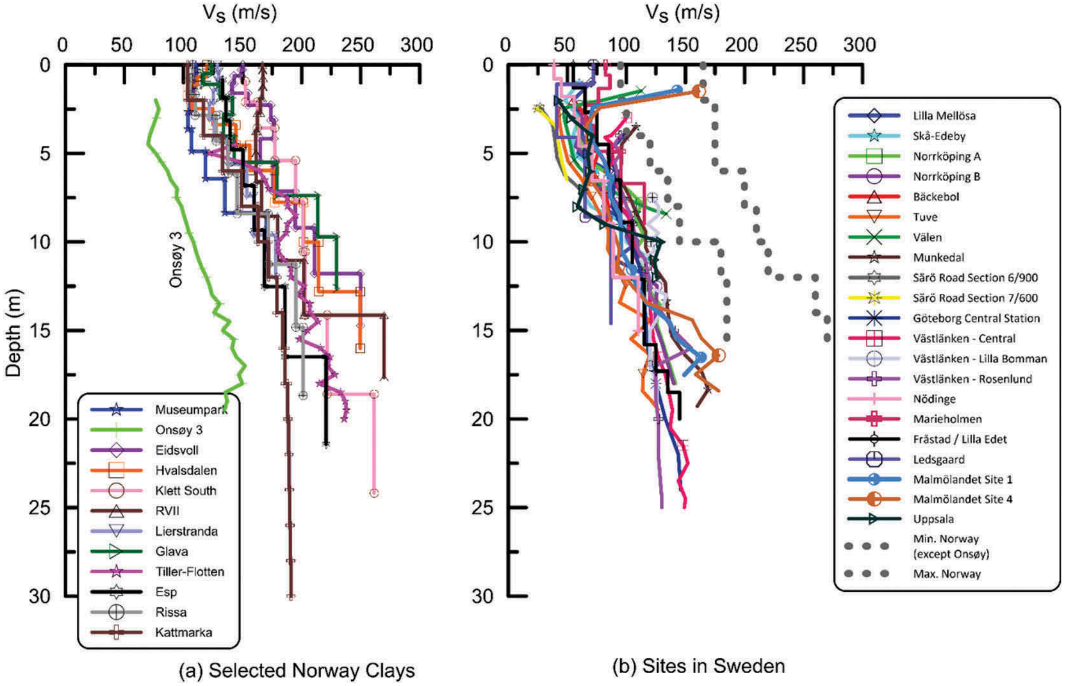


Figure 2. (a) V_s profiles for selected Norwegian sites. Data from L'Heureux and Long (2017) and this paper and (b) for Swedish clays from Long et al. (2017) and Long and D'Ignazio (2020).

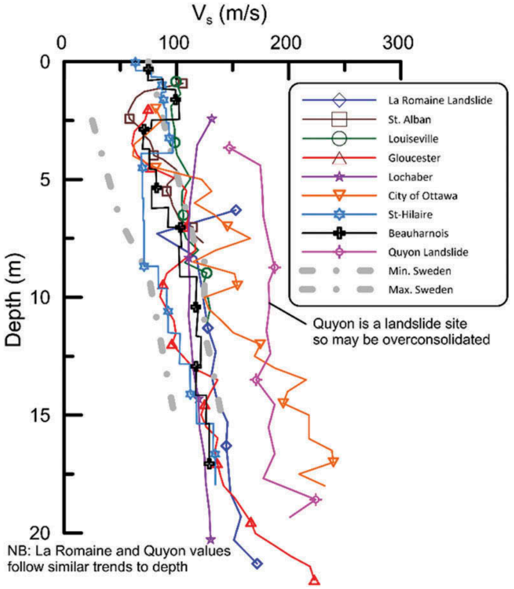


Figure 3. V_s profiles for Eastern Canadian sensitive clays Data from Bouchard et al. (2017), Lefebvre et al. (1994), Leroueil et al. (2003), Mayne et al. (2019), Fabien-Ouellet et al. (2014), Motazedian et al. (2011), Elbeggo et al. (2021) and Agaiby (2018).

These Norwegian sites have relatively lower water content and plasticity and higher density (1.7 – 1.9 Mg/m^3 compared to 1.6 – 1.7 Mg/m^3) than the Canadian and Swedish sites. Also Tiller-Flotten has very low organic content compared to the other sites. The Onsøy site parameters are much closer to those of the Swedish and Canadian sites. All sites under consideration have similar clay content and stress history.

Table 1. Summary of material properties for the study sites: w = water content, I_p = plasticity index, Org. = organic content OCR = overconsolidation ratio, S_t = fall cone sensitivity. Main references Gundersen et al. (2019), L'Heureux et al. (2019), Wood (2016) and Trak et al. (1980).

Site	W (%)	Clay (%)	I_p (%)	Org. (%)	OCR	S_t
Onsøy	40-80	50-70	25-50	2.5-4	1.1-2.0	5-8
Tiller-Flotten	30-50	45-70	8-20	Very low	1.5-2.0	up to 350
Göteborg CS	60-90	70-90	27-40	2-5	1.5-2.0	12-30
St. Alban	60-90	45-81	5-30	0.9	2.2	14-22

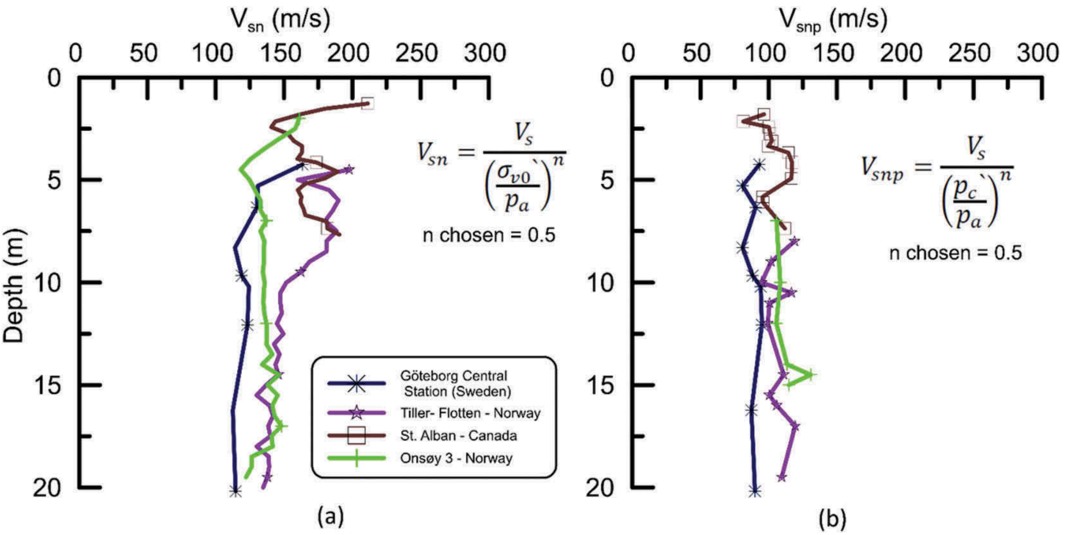


Figure 4. Normalised V_s profiles (a) by vertical effective stress and (b) preconsolidation stress.

5 NORMALISATION OF V_S VALUES

5.1 *Normalisation by vertical effective stress*

According to Hight and Leroueil (2003) and Hardin (1978) the controlling factors on V_s are primarily functions of soil density, void ratio, and effective stress, with secondary influences including soil type, age, depositional environment, cementation and stress history. It is logical then to attempt to harmonise the V_s profiles by normalising them with respect to in situ vertical effective stress (σ_{v0}'). Here the normalised parameter V_{sn} is determined from as follows:

$$V_{sn} = \frac{V_s}{\left(\frac{\sigma_{v0}`}{p_a}\right)^n} \tag{1}$$

Mayne et al. (1998), Robertson (2009) and others have chosen n = 0.25 based mostly on laboratory data on silica sands. Here a value of 0.5 has been chosen. Data from the four selected study sites normalised as above are plotted against depth on Figure 4a. Although the normalisation brings the values from the four study sites closer together there are still significant differences between the values especially those of Tiller-Flotten and St. Alban below about 4 m. The value of n was altered but no improvements in the relationships were observed.

5.2 *Normalisation by preconsolidation stress*

To take the stress history of the materials into account the measured V_s data have been normalised by the preconsolidation stress (p_c') on Figure 4b. A form of normalisation very similar to that expressed in Equation 3 has been used as follows:

$$V_{s2} = \frac{V_s}{\left(\frac{p_c`}{p_a}\right)^{0.5}} \tag{2}$$

Unfortunately, as is well known, p_c' can be heavily influenced by sample disturbance effects and by the method used to determine p_c' from the measured oedometer tests data. To deal with the issue of sample disturbance the sites have been chosen where very high quality samples are available. Data from Sherbrooke block or mini-block samples were available for all four sites. The Casagrande (1936) technique was used to determine p_c' at three of the sites with the Janbu (1969) approach being used for the Göteborg Central Station site. No correction has been applied to the p_c' data. The reported values have been used and compared directly to V_s measurements at the same depth.

As can be seen on Figure 4b this form of normalisation was very successful in harmonising the four sets of data. All four profiles are very similar and show an average V_{snp} value of about 100 m/s. Taking this average V_{snp} value the following equation can be obtained to relate V_s and p_c'.

$$p_c` = 0.01V_s^2 \tag{3}$$

This form of power equation supports and justifies some previous similar empirical equations that have been developed. These include the general relationship developed by Mayne et al. (1998) as shown on Equation 4, that derived for Norwegian marine clays by L'Heureux and Long (2017) (Equation 5) and by Duan et al. (2019) for Jiangsu clays in China (Equation 6)

$$p_c` = 0.106V_s^{1.47} \tag{4}$$

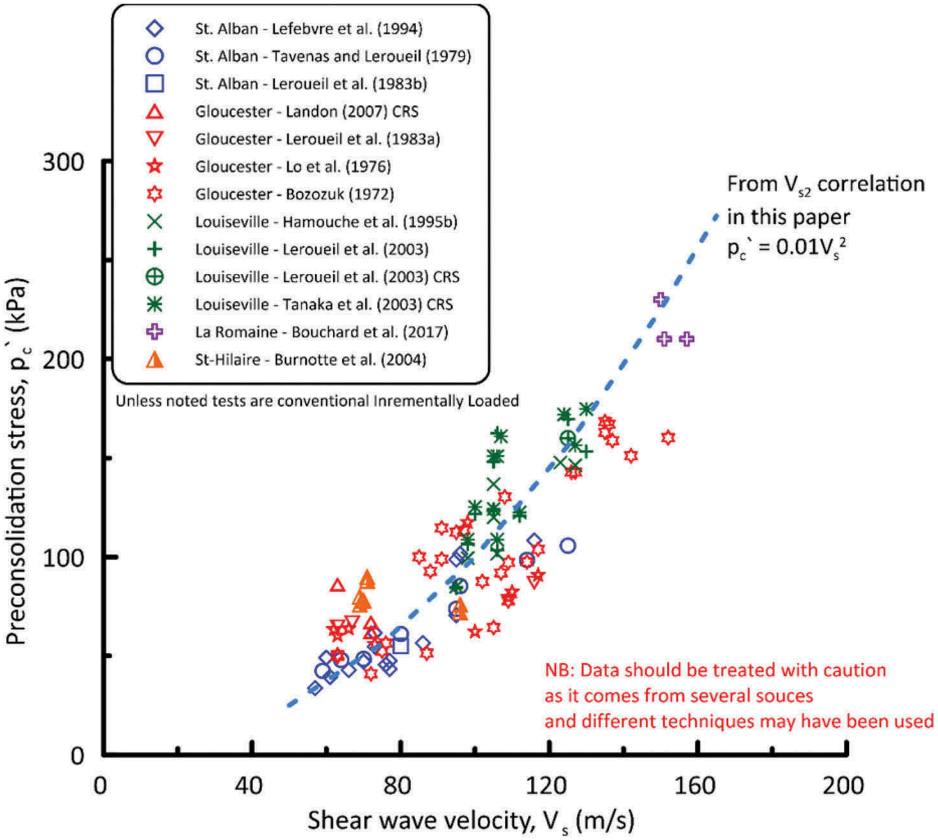


Figure 5. Relationship between V_s and p_c' for Eastern Canada clays. Data from Lefebvre et al. (1994), Tavenas and Leroueil (1979), Leroueil et al. (1983b), Landon (2007), Leroueil et al. (1983a), Lo et al. (1976), Bozozuk (1972), Hamouche et al. (1995), Leroueil et al. (2003), Tanaka et al. (2003), Bouchard et al. (2017) and Burnotte et al. (2004).

$$p_c' = 0.00769 V_s^{2.009} \qquad (5)$$

$$p_c' = 0.1097 V_s^{1.3575} \qquad (6)$$

6 V_S-P_C' RELATIONSHIP FOR EASTERN CANADA CLAYS

Available V_s and parallel p_c' data for Eastern Canada clays is shown on Figure 5. This data should be treated with caution as it comes from several sources and it is possible different sampling techniques, testing techniques and methods of deriving p_c' may have been used. The data is shown merely to illustrate the application and usefulness of Equation 5 and suggests further work on this approach is well warranted.

7 CONCLUSIONS

The purpose of this paper was to highlight some advantages in the use of V_s values in soil characterisation studies and to therefore encourage the use of the SCPTU device. The particular focus here was the derivation of p_c' from V_s data for sensitive marine clays. It was shown that despite V_s profiles for marine clays from different countries being often different, normalisation by p_c' harmonises the different profiles. A rational method, without resorting to empirical correlations, is outline for the derivation of a formula which relates V_s and p_c'. The derived formula is tested successfully on a set of data for Canadian marine clays. More sites should be included in the relationship shown on Figure 4b to study the likely variation in the values determined.

REFERENCES

Agaiby, S. S. (2018) Advancements in the interpretation of seismic piezocone tests in clays and other geomaterials. PhD Thesis, School of Civil and Enironmental Engineering, Georgia Institute of Technology.

Bouchard, S., Ali, H., Leboeuf, D., Leroueil, S. & Cascante, G. (2017) Dynamic properties of sensitive clay deposits. IN Thakur, V., L'Heureux, J.-S. & Locat, A. (Eds.) *2nd International Workshop on Landslides in Sensitive Clays (IWLSC)*.

Bozozuk, M. (1972) The Gloucester test fill. PhD Dissertation, Department of Civil Engineering, Purdue University, West Layfayette, IN, 184.

Burnotte, F., Lefebvre, G. & Grondin, G. (2004) A case record of electrosmotic consolidation of soft clay with improved soil-electrode contact. *Canadian Geotechnical Journal*, 41, 1038–1053.

Casagrande, A. (1936) The determination of the pre-consolidation load and its practical significance. *Proceedings of the 1st International Soil Mechanics and Foundation Engineering Conference*. Cambridge, Massachusetts.

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

Elbeggo, D., Ethier, Y., Dubé, J. S. & Karray, M. (2021) Critical Insights in laboratory shear wave velocity correlations of clays. *Canadian Geotechnical Journal*, Accepted manuscript.

Fabien-Ouellet, G., Fortier, R. & Giroux, B. (2014) Joint acquisition and processing of seismic reflections and surface waves in a sensitive clay deposit in the Outaouais region (Québec), Canada. *1st International Workshop on Landslides in Sensitve* Clays *(IWLSC)*. Québec, Springer.

Gundersen, A. S., Hansen, R. C., Lunne, T., L'heureux, J.-S. & Strandvik, S. O. (2019) Characterization and engineering properties of the NGTS Onsøy soft clay site. *AIMS Geosciences*, 5, 665–703.

Hamouche, K., Leroueil, S., Roy, M. & Luteneger, A. J. (1995) In situ evaluation of K_0 in eastern Canada clays. *Canadian Geotechnical Journal*, 32, 677–688.

Hardin, B. O. (1978) The nature of stress – strain behaviour for soils. *In Proceedings ASCE Speciality Conference on Earthquake Engineering and Soil Dynamics, Pasadena, California*.

Hight, D. W. & Leroueil, S. (2003) Characterisation of soils for engineering purposes. IN Tan, T. S., Phoon, K. K., Hight, D. W. & Leroueil, S. (Eds.) *Proceedings International Workshop on Charaterisation and Engineering Properties of Natural Soils*. Singapore, Balkema, Rotterdam.

Janbu, N. (1969) The resistance concept applied to deformations of soils. *Proceedings of the 7th International Soil Mechanics and Foundation Engineering Conference*. Mexico City, A.A. Balkema, Rotterdam.

L'heureux, J.-S., Lindgård, A. & Emdal, A. (2019) The Tiller-Flotten research site: Geotechnical characterisation of a sensitive clay deposit. *AIMS Geosciences*, 5, 831–867.

L'heureux, J.-S., Lunne, T., Lacasse, S., Carroll, R., Strandvik, S. O., Ozkul, Z., Instanes, A., Sinitsyn, A., Degago, S. A. & Nordal, S. (2017) Norway's National GeoTest Site Research Infrastructure (NGTS). *19th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE)*. Seoul.

L'heureux, J.-S. & Long, M. (2017) Relationship between shear wave velocity and geotechnical parameters for Norwegian clays. *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 04017013-1 – 04017013–20.

Landon, M. E. (2007) Development of a non destructive sample quality assessment method for soft clays. *PhD Thesis, Department of Civil and Environmental Engineering, University of Massachusetts*, *Amherst*. PhD Thesis, Department of Civil and Environmental Engineering, University of Massachusetts, Amherst.

Lefebvre, G., Beloueuf, D., Rahhal, M. E., Lacroix, A., Warde, J. & Stokoe, K. H. (1994) Laboratory and field determinations of small-strain shear modulus for a structured Champlain clay. *Canadian Geotechnical Journal*, 31, 61–70.

Leroueil, S., Hamouche, K., Tavenas, F., Boudali, M., Locat, J., Virely, D., Roy, M., La Rochelle, P. & Leblond, P. (2003) Geotechnical characterisation and properties of a sensitive clay from Québec. IN Tan, T. S., Phoon, K. K., Hight, D. W. & Leroueil, S. (Eds.) *Proceedings International Workshop on Charaterisation and Engineering Properties of Natural Soils*. Singapore, Balkema, Rotterdam.

Leroueil, S., Samson, L. & Bozozuk, M. (1983a) Laboratory and field determination of preconsolidation pressures at Gloucester. *Canadian Geotechnical Journal*, 20, 477–490.

Leroueil, S., Tavenas, F., Samson, L. & Morin, P. (1983b) Preconsolidation pressure of Champlain clays, Part 2, Laboratory determination. *Canadian Geotechnical Journal*, 20, 803–816.

Lo, K. Y., Bozozuk, M. & Law, K. T. (1976) Settlement analysis of the Gloucester test fill. *Canadian Geotechnical Journal*, 13, 339–354.

Long, M. & D'ignazio, M. (2020) Shear wave velocity as a tool for characterising undrained shear strength of Nordic clays. *18th Nordic Geotechnical Meeting*. Helsinki, Finland (Conferece held virtually January 2021), IOP Conf. Series: Earth and Environmental Science 710 (2021) 012008.

Long, M., Wood, T. & L'heureux, J.-S. (2017) Relationship between shear wave velocity and geotechnical parameters for Norwegian and Swedish sensitive clays. *2nd International Workshop on Landslides in Sensitive Clays (IWLSC)*.

Mayne, P. W., Cargill, E. & Miller, B. (2019) Geotechnical characteristics of sensitive Leda clay at Canada test site in Gloucester, Ontario. *AIMS Geosciences*, 5, 390–411.

Mayne, P. W., Robertson, P. K. & Lunne, T. (1998) Clay stress history evaluated from seismic piezocone tests. IN Robertson, P. K. & Mayne, P. W. (Eds.) *Proceedings 1st. International Conference on Geotechnical Site Characterisation*. Atlanta, Georgia, Balkema.

Motazedian, D., Hunter, J. A., Pugin, A. & Crow, H. (2011) Development of a Vs30 (NEHRP) map for the city of Ottawa, Ontario, Canada. *Canadian Geotechnical Journal*, 48, 458–472.

Ólafsdóttir, E. A., Bessason, B., Erlingsson, S., L'heureux, J.-S. & Bazin, S. (2019) Benchmarking of an open-source MASW software using data from three Norwegian GeoTest Sites. *17th European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE)*. Reykjavik, Iceland.

Park, C. B., Miller, D. M. & Xia, J. (1999) Multichannel analysis of surface waves. *Geophysics*, 64, 800–808.

Robertson, P. K. (2009) Interpretation of cone penetration tests - a unified approach. *Canadian Geotechnical Journal*, 46, 1337–1355.

Tanaka, H., Shiwakoti, D. R. & Tanaka, M. (2003) Applicability of SHANSEP method to six different natural clays using triaxial and direct shear tests. *Soils and Foundations*, 45, 43–55.

Tavenas, F. & Leroueil, S. (1979) Clay behaviour and the selection of design parameters. *7th European Conference on Soil Mechanics and Foundation Engineering (ECSMFE)*. Brighton, UK.

Trak, B., La Rochelle, P., Tavenas, F., Leroueil, S. & Roy, M. (1980) A new appeoach to the stability analysis of embankments on sensitive clays. *Canadian Geotechnical Journal*, 17, 526–544.

Wood, T. (2016) On the small strain stiffness of some Scandinavian soft clays and impact on deep excavations, PhD thesis Department of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg, Sweden.