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Evaluation of existing CPTu-based correlations for the deformation properties of Finnish soft clays

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ABSTRACT: An extensive research program for soil testing has been conducted on five soft clay deposits located in Finland. This research project aims to collect data from high quality *in-situ* and laboratory tests and derive correlations for the strength and deformation properties specific to Finnish clays. In the literature, several authors have proposed correlation models for the deformation properties of soft clays based on CPTu measurements. However, such models are often calibrated for a specific site or a specific soil type. Consequently, these models must be validated before applying them to different soil conditions. In this paper, existing correlations for the deformation properties of soft clays based on CPTu data are compared to the test results from the investigated sites. The validity of the existing models is assessed for Finnish clays by evaluating their bias and uncertainties.

1 INTRODUCTION

The cone penetration test (CPTu) offers the ability to quickly and economically evaluate subsurface soil conditions. The traditional piezocone test provides continuous and independent measurement of three different parameters: cone tip resistance (q_c), sleeve friction (f_s), and pore water pressure (u) in saturated soils. Moreover, sensors can be added to the traditional probe to obtain additional data. For instance, with seismic piezocone (SCPTu) and resistivity piezocone (RCPTu), it is possible to profile shear wave velocity and electrical conductivity, respectively.

Even though the CPTu test is widely used in Scandinavia, the field vane (FV) shear test is still the most commonly employed *in-situ* investigation tool in Finland to determine undrained shear strength (s_u). Deformation properties, such as stiffness and/or preconsolidation pressure (σ'_p), are generally evaluated using constant-rate-of-strain (CRS) oedometer tests.

Tampere University of Technology (TUT) purchased a piezocone equipped with seismic and resistivity cones in order to establish the CPTu correlations for the strength and deformation properties of Finnish soft clays. Preliminary results have been reported by Di Buò et al. (2016).

Various empirical correlations have been proposed in the literature for determining geotechnical parameters based on CPTu data (e.g., Kulhawy and Mayne, 1990; Chen and Mayne, 1996; Karlsrud et al., 2005; L'Heureux and Long, 2017). However, in practice, the use of such correlations to evaluate local soil conditions requires validation and, possibly, calibration.

The main goal of the present study is to verify the validity of existing global and regional CPTu-based correlations for the deformation parameters of soft clays. A data set consisting of high quality laboratory and *in-situ* data gathered by TUT is exploited to verify these correlations in Finnish soil conditions. The analysis focused on the deformation parameters determined from CRS oedometer tests on soft clay samples from five sites in Finland. The bias and uncertainties of the correlations are evaluated with respect to the data set.

2 TEST SITES

This paper presents the results from the investigation conducted on five different soft clay test sites located in Southern Finland. The main geotechnical properties, including natural water content (w), plasticity index (PI), overconsolidation ratio (OCR), and sensitivity (S_t) are shown in Table 1.

The Perniö test site is located on the southwestern coast of Finland, next to the railway track connecting the cities of Helsinki and Turku. The stratigraphy consists of a 1.5 m thick dry crust layer overlaying an 8–9 m thick soft clay layer.

Table 1. Geotechnical properties of the five investigated sites.

SITE	z (m)	*w* (%)	*PI*	*OCR**	S_t**
Perniö	2–3	100–120	40	2	40–60
	3–6	70–90	20–30	1.3–1.6	40–50
	6–8	90–100	40	1.3–1.4	50–70
Lempäälä	3–4	110–130	40	1.2–1.5	30–40
	4–8	60–80	20–30	1.2–1.4	30–50
Masku	3	80–90	40	1.5–1.7	20
	5	110–120	60–70	1.5	20
	8	70–80	40	1.2–1.5	20
Paimio	3–6	50–80	20	1.6–1.8	80–100
	6–9	90–110	30–40	1.3–1.4	60–80
Sipoo	2–4	80–90	40–50	1.7–1.9	20–40
	4–9	100–120	50–60	1.3–1.5	20–30

**OCR* determined from the CRS tests; **S_t determined from the Fall Cone (FC) test.

The clay content varies from 60% at a depth of 3 m to 90% at a depth of 8 m. The organic content is less than 1%. The site has been previously investigated and results are reported by Lehtonen (2011) and D'Ignazio et al. (2015).

The Lempäälä site is located near the city of Tampere, along the railway track to Helsinki. The deposit consists of a 1.5 m thick layer of weathered clay crust followed by 1.5 m of organic soil overlaying soft sensitive clay. The clay content is approximately 60% and the organic content is approximately 5% above a depth of 3 m and less than 1% in the soft clay.

The Masku test site is located on the southwestern coast of Finland, near the city of Turku. The stratigraphy consists of 1.5 m of weathered clay crust over an 11 m thick soft clay deposit. Masku clay is the least sensitive ($S_t = 20$) among the clays presented in this study. The clay content varies between 60% and 90%. The organic content is less than 2%.

The Paimio site is located close to the city of Turku, in the southwestern region of Finland. The stratigraphy consists of a 2 m thick dry crust over a 10 m thick soft clay deposit. Two soft clay layers with different properties were found: a leaner upper clay layer and a lower layer of more plastic clay with a higher *w*. The clay content of the top layer ranges between 40% and 60%, increasing up to almost 100% at greater depths. The organic content of the entire deposit is less than 1%.

The Sipoo test site is located 30 km north of the city of Helsinki. Index test results reveal the presence of a deposit of homogeneous soft clay with a depth ranging between 2 m and 9 m characterized by the highest *PI* values among all the five investigated sites (*PI* = 60). The clay content increases as the depth increases, from approximately 60% at a depth of 3 m to 90% at a greater depth. The organic content is consistently lower than 2% throughout the deposit.

3 EXPERIMENTAL PROGRAM

The investigation included both *in-situ* and laboratory tests conducted on undisturbed samples from the five test sites mentioned above. The field investigation was conducted using a CPTu equipped with a seismic and resistivity cone and FV (Di Buò et al., 2016; Selänpää et al., 2017). The penetrometer consists of a standard 60° apex conical tip with a 150 cm^2 sleeve area. Excess pore pressure is measured at the shoulder above the cone tip (u_2). Details about the equipment and test procedures are described in Di Buò at al. (2016). Two different cones were used: a high capacity cone (75 MPa) and a "sensitive" cone (7.5 MPa). The latter is considered more suitable in a soft soil condition. The CPTu measurements from the Perniö site are shown in Figure 1. In particular, the corrected cone tip resistance, sleeve friction, and pore pressure are plotted versus the depth. Overall, the measurements show very good repeatability even though some scatter can be observed, especially for the high capacity cone data. Moreover, the resolution of the sleeve friction is not adequate since the sensor is not able to measure small changes of the recorded value. Therefore, improvement of the apparatus is suggested to improve the quality of the data.

The laboratory tests included classification and index tests for the remolded samples, the CRS oedometer test, the triaxial test, and the direct simple shear (DSS) test for the intact samples. In this paper, the results from the CRS tests are used to evaluate the compressibility (oedometer modulus, M_0) and stress-history (σ'_p) of the tested soils. The CRS oedometer tests were performed on samples with a 45 mm diameter and a 15 mm thickness at a constant strain rate of 0.001 mm/min (0.4%/h).

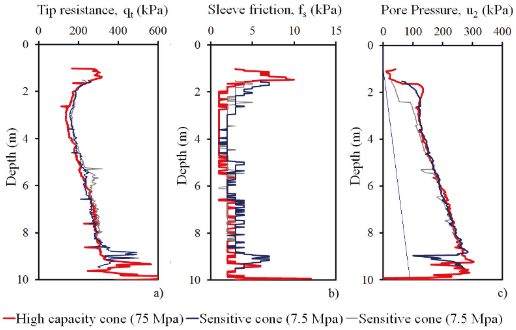

Figure 1. CPTu measurements at the Perniö site: a) corrected cone tip resistance, q_t; b) sleeve friction, f_s; c) pore pressure, u_2.

It is important to note that three different samplers were used to retrieve the soil samples: a mini-block Sherbrook sampler (Emdal et al., 2016), an open drive 132 mm diameter tube (TUT 132), and an ordinary STI 50 mm piston sampler. The tube sampler was developed at TUT in 2014 (Di Buò et al., 2016); it was inspired by the Laval tube sampler (La Rochelle et al., 1981) and its modification by the Swedish Geotechnical Institute (SGI) (Larsson, 2011). Figure 2 and Table 2 show the achieved sample quality based on Lunne et al.'s (1997) criteria. In general, the block had the highest quality of all the tested samples.

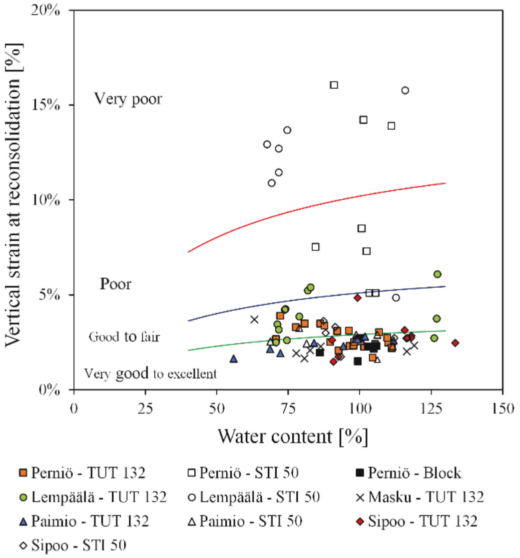

Figure 2. Sample quality based on Lunne et al.'s (1997) criteria.

Table 2. Sample quality based on Lunne et al.'s (1997) criteria.

		Number of CRS oedometer tests				
Site	Sampler	Tot.	Excellent	Good to fair	Poor	Very poor
Perniö	STI 50	8	–	2	3	3
	TUT 132	22	13	9	–	–
	Block	6	6	–	–	–
Lempäälä	STI 50	8	–	2	–	6
	TUT 132	11	3	5	3	–
Masku	TUT 132	7	6	1	–	–
Paimio	STI 50	7	6	1	–	–
	TUT 132	9	9	–	–	–
Sipoo	STI 50	6	3	3	–	–
	TUT 132	9	7	2	–	–
Total		93	53	25	6	9

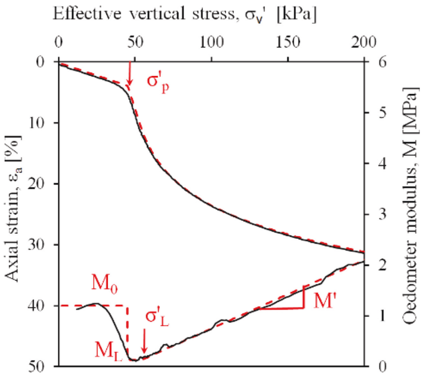

Figure 3. Schematization of Sällfors' (1975) method used to interpret preconsolidation pressure from the CRS tests.

However, good quality samples could be also obtained from the STI 50 piston sampler, especially at Paimio and Sipoo. Sample quality plays an important role in the calibration of empirical correlations since the evaluation of geotechnical parameters can be greatly affected by disturbance induced during sampling, transportation, and storage (Lunne et al., 1997; Lunne et al., 2006; Amudsen et al., 2016).

A total of 93 CRS oedometer tests were performed. However, 15 tests, which were characterized as having poor and very poor quality, were not considered in the calculations in order to obtain more reliable correlations.

The σ'_p and the oedometer moduli were evaluated using a curve fitting procedure applied to the constrained modulus proposed by Sällfors (1975), as shown in Figure 3.

In the following section, the validity of some of the existing empirical correlations for the deformation properties of clay soils is checked against the data set of the Finnish clays presented in this study. Since Finnish data were not included in the data sets from which these correlations were derived, it is expected that the data points will not always fall in the applicability domain. Therefore, this paper discusses the calibration and validation of the empirical correlations.

4 EVALUATION OF EXISTING CORRELATIONS

4.1 *Bias and uncertainties of the existing correlations*

This section presents an evaluation of the Bias factor (denoted by *b*) and coefficient of variation (*COV*) for the examined correlations based on the procedure reported by Ching and Phoon (2012). In this procedure, *b* and *COV* are calculated as the sample mean and the coefficient of variation, respectively, of the ratio (actual target value)/(predicted target value), where the actual target value is the value measured in a test and the predicted target value is the value predicted by the correlation. If $b = 1$, the model prediction is unbiased.

4.2 *Correlations for OCR and σ'$_p$*

Correlations for the evaluation of OCR and σ'_p from CPTu are available in the literature (Kulhawy and Mayne, 1990; Larsson and Mulabdic, 1991; Chen & Mayne, 1996; Karlsrud et al., 2005).

For intact clays, a correlation to evaluate the OCR based on normalized cone tip resistance (Q_t) was suggested by Kulhawy and Mayne (1990) as:

$$OCR = k\left(\frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\right) = kQ_t \tag{2}$$

where q_t is the corrected cone tip resistance, σ_{v0} is the total overburden vertical stress, and k is an empirical parameter. An average value of $k = 0.33$ is suggested by Kulhawy and Mayne (1990) based on statistical analysis of piezocone-oedometer data involving a variety of different clays located mainly in the United States, the United Kingdom, and Canada.

A similar correlation was proposed by Karlsrud et al. (2005) based on a database of 17 high sensitive clay deposits located in Norway:

$$OCR = \left(\frac{Q_t}{2}\right)^{1.11} \tag{3}$$

Both correlations are plotted in Figure 4, and the results are compared with the experimental data. As shown in Figure 4, Equation 2 gives an almost unbiased prediction (b = 1.07), accompanied by a low variability (COV = 0.15). However, Equation 3 seems to over-predict the OCR of Finnish clays by nearly 40% (b = 0.65).

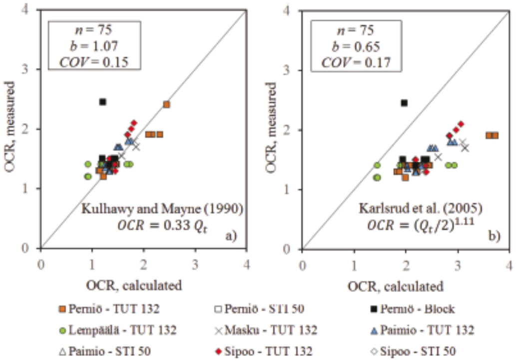

Figure 4. Comparison of the empirical correlations and the experimental data to evaluate OCR: a) Kulhawy and Mayne (1990); b) Karlsrud et al. (2005).

Chen and Mayne (1996) proposed simple relationships to determine σ'_p from the CPTu data as:

$$\sigma'_p = 0.53\left(u_2 - u_0\right) = 0.53\ \Delta u \tag{4}$$

$$\sigma'_p = 0.60\left(q_t - u_2\right) \tag{5}$$

Similarly, σ'_p can be evaluated from $q_{net} = q_t - \sigma_{v0}$ using the following equation:

$$\sigma'_p = \frac{q_t - \sigma_{v0}}{N_{kT(\sigma'_p)}} \tag{6}$$

where $N_{kt(\sigma'p)}$ is an adapted cone factor. For Swedish clays, Larsson and Mulabdic (1991) proposed $N_{kt(\sigma'p)}$ as a function of the liquid limit (LL) as:

$$N_{kt(\sigma'_p)} = 1.21 + 4.4\ LL \tag{7}$$

As shown in Figure 5, Equation 4 gives the lowest COV, thus indicating that an evaluation of σ'_p based on Δu is generally more reliable. While Equation 4 overestimates the σ'_p of Finnish clays by 25%

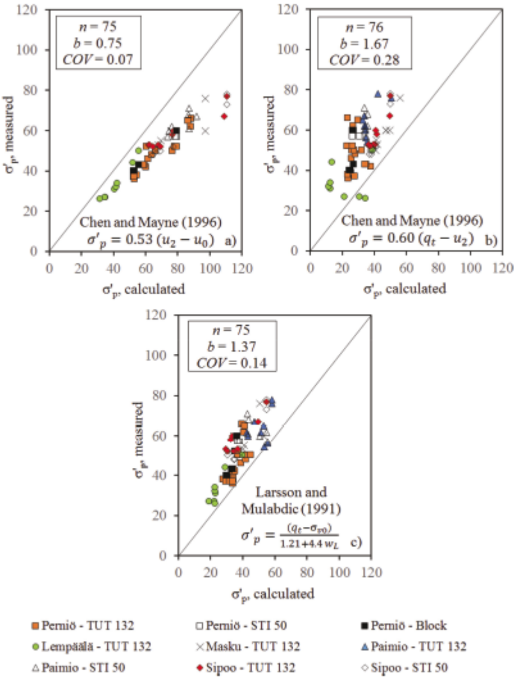

Figure 5. Comparison of the empirical correlations and the experimental data to evaluate σ'_p: a) Chen and Mayne (1996); b) Chen and Mayne (1996); c) Larsson and Mulabdic (1991).

(b = 0.75), Equation 5 and Equation 6 underestimate σ'_p by 61% and 15%, respectively. Therefore, Equations 4–6 need to be adjusted based on the calculated b values in order to be usable in Finnish clays.

4.3 *Correlations for constrained modulus*

The soil stiffness in one-dimensional compression can be expressed in terms of the constrained modulus (M), which is defined as the ratio of the change in effective stress ($\Delta\sigma'_v$) to the change in strain ($\Delta\varepsilon_v$):

$$M = \frac{\Delta\sigma'_v}{\Delta\varepsilon_v} \tag{8}$$

The constrained modulus is stress-dependent; in the overconsolidated part, a relatively high value (M_0) can be found, while the modulus drops significantly when the preconsolidation pressure is exceeded (Figure 3). In practice, the modulus in the overconsolidated part can often be modelled as a constant value. In this paper, only the constant M_0 modulus is evaluated.

Using an extensive database of silts, sands, and fine-grained soils, Mayne (2006) proposed an empirical correlation to evaluate the constrained modulus at the *in-situ* stress state (M_0) from the net cone tip resistance given by:

$$M_0 = \alpha(q_t - \sigma_{v0}) = \alpha q_{net} \tag{9}$$

The representative value of α depends on the nature of the soil. Considerably low values of α (α ≈ 1–2) are suggested for organic plastic clays from Sweden, while higher values (α >10) are expected for cemented clays. Figure 6 shows the plot of M_0 versus (q_t − σ_{v0}) for the clays investigated in the present study. As seen, the majority of data points fall between the trend lines for α that are equal to 5 and 10. Clearly, as discussed earlier, for σ'_p, the value of M is affected by the sample quality (e.g., Lunne et al., 2006; Karlsrud and Hernandez-Martinez, 2013). It is important to point out that the mean trend of the sites characterized by the highest sample quality (Paimio, Sipoo, and Masku) can be captured using α ≈ 10. However, the lower values of α seem to be more representative of the other sites. Further investigation is required to evaluate the effect of soil conditions and, possibly, sample quality on α.

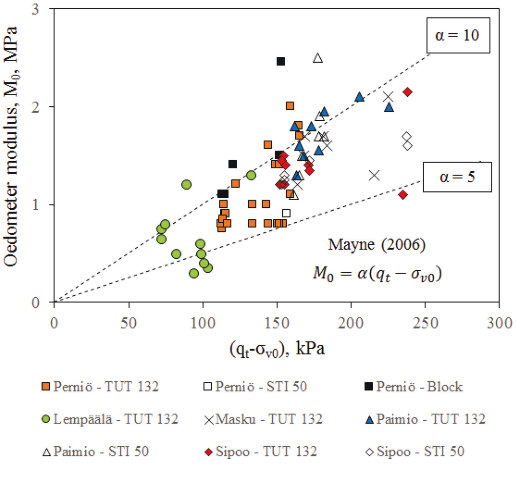

Figure 6. Comparison of the empirical correlations and the experimental data to evaluate the constrained modulus (M_0).

4.4 *Correlations between shear wave velocity and key geotechnical parameters*

The measurement of shear wave velocity (V_s) can be performed by adding geophones to the SCPTu. This provides the possibility of estimating the small-strain shear modulus (G_{max}) as:

$$G_{max} = \rho V_s^2 \tag{10}$$

where ρ is the soil density. Moreover, V_s can be used to estimate the geotechnical parameters (Mayne and Rix, 1995; Robertson, 2009; Mayne, 2014; L'Heureux and Long, 2017). In this section, the relationships between V_s and the 1D compression parameters are compared to existing correlations in the literature. In particular, the relationships between M_0, σ'_p, and V_s are analyzed. L'Heureux and Long (2017) proposed empirical correlations based on a database of 28 Norwegian clay sites. They suggested that M_0 and σ'_p increase as V_s increases, as shown by Equation 10 and Equation 11:

$$\sigma'_p = 0.00769\, V_s^{2.009} \tag{11}$$

$$M_0 = 0.00010\, V_s^{2.212} \tag{12}$$

The information presented in Figures 7a, b confirms the trends reported by L'Heureux and Long (2017) for Norwegian clays, despite the high values of b and COV. It is important to note that the correlations reported by L'Heureux and Long (2017) are based on clays that are characterized by higher OCR and S_t in comparison to the clays examined in the present study.

Equations similar to (11) and (12) can also be derived theoretically. The relationship between the oedometer modulus (M_0) and the shear modulus (G) is given by:

$$M_{oed} = \frac{2(\upsilon - 1)}{(2\upsilon - 1)} G \tag{13}$$

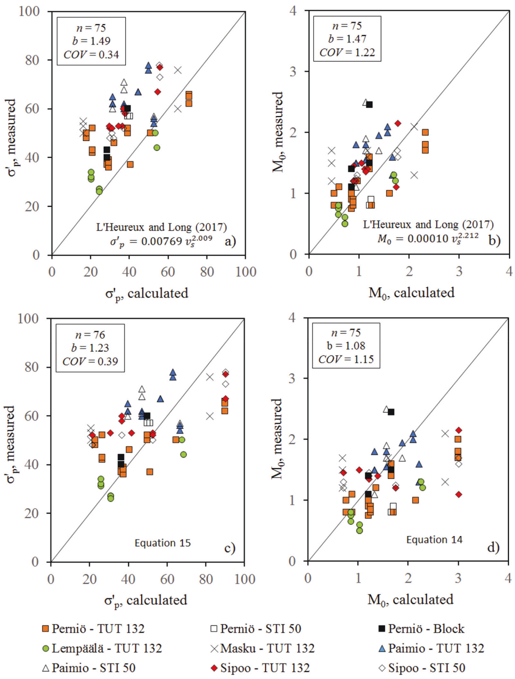

Figure 7. Comparison of the correlations based on shear wave velocity and the experimental data for the evaluation of: a) preconsolidation pressure evaluated based on L'Heureux and Long (2017); b) constrained modulus M_0 evaluated based on L'Heureux and Long (2017); c) preconsolidation pressure evaluated with Equation 14; d) constrained modulus M_0 evaluated using Equation 13.

where υ is the Poisson's ratio, which can be assumed to be 0.1 for small-strain stiffness corresponding to G_0. Considering a scaling factor of 10, to take into account the modulus degradation with increasing strain, M_0 is obtained as:

$$M_0 = \frac{1}{10}\frac{2(\upsilon-1)}{(2\upsilon-1)}\rho V_s^2 = 0.225\,\rho V_s^2 \qquad (14)$$

where ρ is the soil density assumed as constant (1500 kg/m^3) in the present study.

Similarly, σ'_p can be estimated assuming that the yield stress is reached at 3% of the vertical deformation. Therefore:

$$\sigma'_p = 0.03\, M_0 = 0.00675\,\rho V_s^2 \qquad (15)$$

Both σ'_p and M_0 are expressed in Pa, while the unit measure of V_s is m/s. Equation 15 and Equation 14 are plotted in Figure 7c and 7d, respectively. Despite the high scatter, the theoretical solutions seem to fit better the mean trend of the Finnish clay data points in comparison to Equation 11 and Equation 12 ($b = 1.23$–1.08 vs $b = 1.49$–1.47).

As mentioned earlier, the influence of sample quality and the intrinsic uncertainty associated with geophysical measurements need to be further investigated before calibrating an empirical correlation valid in Finnish clay conditions.

5 CONCLUSIONS

This paper aimed to present CPTu and laboratory measurements obtained from Finnish soft clay deposits and evaluate the validity of existing empirical correlations to assess the deformation parameters of soft clays. Laboratory data from high quality samples were used. The main conclusions from this work are:

- The correlations for *OCR* from the CPTu evaluated in this study can describe the behavior of Finnish soft clays with relatively low uncertainty (*COV* = 12–14%). In particular, the correlation reported by Kulhawy and Mayne (1990) resulted in an almost unbiased prediction. A wider range of bias factors ($b = 0.75$–1.61) and *COVs* (8–31%) was found for the correlations based on σ'_p.
- The link between soil stiffness, expressed in terms of constrained modulus, M_0, and the net cone tip stress fits well with established empirical correlations for clays worldwide (Mayne, 2006). However, the data show significant scatter; this might be partly due to variations in the sample quality. Further investigation is required to calibrate a model valid for Finnish clays, which also accounts for the nature of the soil.
- Both preconsolidation pressure and constrained modulus can be evaluated based on the shear wave velocity. The empirical correlations reported by L'Heureux and Long (2017) seem to describe the trend between these parameters, but the scatter is quite high. The prediction could be slightly improved using similar, but theoretically derived equations.

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