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Piezocone testing in Nordic soft clays: Comparison of high-quality databases

M. D’Ignazio & B. Di Buò
Tampere University, Tampere, Finland
Ramboll Finland Oy, Tampere, Finland

T. Länsivaara
Tampere University, Tampere, Finland

J.-S. L’Heureux & P. Paniagua
Norwegian Geotechnical Institute, Trondheim, Norway

J. Selänpää
Destia Oy, Tampere, Finland

ABSTRACT: Soft and sensitive clays are widespread in Scandinavia. Piezocone correlations for Norwegian clays have been previously proposed based on high-quality block samples from several sites. Recently, a large database of Finnish soft clays was compiled by Tampere University from piezocone measurements as well as high-quality laboratory tests on specimens from large tube samples. Finnish and Norwegian clays exhibit some differences in terms of basic properties. Norwegian clays show lower water content, lower organic content, higher silt content and lower plasticity than the clays from Finland. This may be linked to the source of the materials, their depositional and post-depositional processes that in turn impact on the mechanical behaviour.

This paper aims to compare piezocone Norwegian and Finnish data with focus on strength and stress history. The database trends are compared for relevant engineering parameters. The data and its variability are critically discussed considering differences in geological history, basic properties, sampling techniques and disturbance.

1 INTRODUCTION

Piezocone (CPTU) testing is one of the most reliable site investigation tools in soft clays, as it has proven repeatability of measurements and can be used to detect soil layering and derive a large number of geotechnical parameters (e.g., Lunne et al. 1997a, Robertson 2009, Di Buò 2019). During cone penetration, the standard CPTU equipment measures cone tip resistance q_c, sleeve friction f_s and excess pore pressure above the cone tip u_2.

The use of CPTU is widespread in Norway, regardless of the project size. CPTU correlations for Norwegian clays derived from high-quality laboratory data on block samples (Karlsrud et al. 2005, Paniagua et al. 2019) have been in use for nearly two decades. On contrary, CPTU testing is still on the rise in Finland, where weight soundings, dynamic penetration testing and field vane testing are among the most preferred site investigation tools. This is mainly a consequence of the lack of local correlations as well as limited experience by the operators. Nevertheless, in recent years the Tampere University (TUNI) has carried out studies on CPTU testing and correlations in Finnish soft clays (Di Buò et al. 2016, Di Buò et al. 2018, Selänpää et al. 2018, Di Buò 2020, Di Buò et al. 2020, Selänpää 2021). The calibration database includes testing on large tube samples retrieved with a Laval-type tube sampler developed by Tampere University (Di Buò et al. 2019). Both the Norwegian and the Finnish databases include laboratory index tests, constant-rate-of-strain (CRS) oedometer tests, undrained triaxial compression (CAUC) and extension tests (CAUE) and direct simple shear tests (DSS).

The scope of this paper is to compare the Norwegian and Finnish clay data to better understand how the basic clay properties impact on the CPTU response in these clays. The database trends are compared for two key engineering parameters, i.e. undrained shear strength and overconsolidation ratio. The observations in terms of cone factors and calibration coefficients are critically discussed, considering differences in basic properties, geological history, sampling techniques and features of the databases.

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2 GEOLOGICAL HISTORY OF NORDIC CLAYS

A detailed study on the geological formation of fine-grained sediments in Finland was conducted by Gardemeister (1975). Fine-grained soil sediments in Finland originated in the late Pleistocene, during the retreat of the continental ice sheet in the Weichselian ice age (11,700 years ago). The entire Scandinavian region was covered by a large ice sheet named Fenno-Scandian that spread out from the Scandinavian Mountains to Northwest Russia, UK, and The Netherlands. The stratigraphy of Finnish soil deposits is the result of a series of processes that occurred at the end of the last glacial period when the Fenno-Scandian ice sheet retreated and during the Holocene (i.e. c. last 10,000 years ago). The glacier meltwater accumulated between the front of the ice sheet and the southern shores, giving rise to what currently is the Baltic Sea. This area underwent four environmental stages in the postglacial progression of the Baltic basin, known as Baltic Ice Lake, Yoldia Sea, Ancylus Lake, and Littorina Sea. (Gardemeister 1975)

Despite the extensive studies conducted on this topic, the process of the formation of the Baltic Sea is not completely clear. Its connection with the Atlantic Ocean during the different phases made the salinity vary with location, depth, and time. The complex origin and development of this area may explain the different geotechnical properties characterizing the clay deposits located in Finland and Sweden compared with the Norwegian ones. The Baltic Ice Lake originated during the retreat of the Weichselian glacier, when meltwater accumulated and formed a freshwater lake. At this stage, the connections with the North Sea and the Atlantic Ocean were closed because the ground on the entire depression rose faster than the sea level. However, a short connection with the sea across central Sweden occurred during the Yoldia Sea stage. At the early stage, the depositional environment was still characterized by low salinity owing to the heavy water flow from the continental ice sheet. The salinity increased after 200 years of the ingression of salt water, creating the condition for a brackish depositional environment. Afterward, the isostatic uplift of the Baltic basin closed the connection with the Atlantic Ocean and the Yoldia Sea turned into Ancylus Lake. This stage lasted until a new connection with the North Sea was established owing to the continuous rising of the water level of Ancylus Lake, forming the Littorina Sea. Finally, the continuous land rise made the connection with the Ocean shallower, thus creating the conditions for the formation of the current Baltic Sea, which is characterized by brackish water. (Gardemeister 1975)

It is evident that the combination of the sea water intrusion and freshwater flow from the melting glacier created a heterogeneous depositional environment characterized by variable salinity content. Although the salt leaching process is considered as the main factor explaining the high sensitivity of Scandinavian marine clays, further studies are needed for Finnish clays.

3 EVALUATION OF ENGINEERING PROPERTIES OF CLAY FROM CPTU

3.1 *CPTU parameters*

Engineering properties of clays are derived from both measured and normalized CPTU parameters. Among these:

- Normalized cone resistance $Q_t=(q_t-\sigma_v)/\sigma'_v$
- Normalized excess pore pressure $Q_u=(u_2-u_0)/\sigma'_v$
- Normalized effective cone resistance $Q_e=(q_t-u_2)/\sigma'_v$
- Pore pressure ratio $B_q=(u_2-u_0)/(q_t-\sigma_v)$

where q_t is the corrected cone tip resistance, σ_v is the total overburden vertical stress, σ'_v the vertical effective stress, u_2 the pore pressure measured above the cone tip, u_0 the in-situ pore pressure.

In addition, $(q_t-\sigma_v)$, (u_2-u_0) and (q_t-u_2) are commonly referred to as q_{net}, Δ_u and q_e, respectively.

3.2 *Overconsolidation ratio*

The over-consolidation ratio (OCR) is defined as the ratio of effective preconsolidation stress σ'_p and the vertical effective stress σ'_v. Several authors verified the dependence of σ'_p and OCR on the cone tip resistance and excess pore pressure parameters, with σ'_p and OCR increasing with increasing q_{net}, σu, q_e and Q_t, Q_u, Q_e respectively. (e.g. Chen and Mayne 1996, Lunne et al. 1997, D'Ignazio et al. 2019).

In practice, the relationship between σ'_p and q_{net} is the most used (Equation 1). The relationship between OCR and Q_t is used in the same way as (Equation 2):

$$\sigma'_p = k(q_t - \sigma_v) = kq_{net} \tag{1}$$

$$OCR = k\frac{q_t - \sigma_v}{\sigma'_v} = k\frac{q_{net}}{\sigma'_v} = kQ_t \tag{2}$$

where k is an empirical parameter. Similar equations are found in the literature for Δu, q_e and Q_u, Q_e. An average value of $k \approx 0.32$ is suggested by Chen and Mayne (1996) based on statistical analysis of piezocone-oedometer data involving a variety of different clays. D'Ignazio et al. (2019) found k in the range 0.15-0.5 for clays with OCR ≈ 1-5. Paniagua et al. (2019) found k = 0.20-0.75 for Norwegian clays, while Di Buò (2019) suggested k = 0.28 with coefficient of variation (COV) ≈ 0.1 for Finnish soft clays.

3.3 *Undrained shear strength*

The net cone resistance q_{net} is related to the undrained shear strength s_u by means of the cone factor N_{kt} as:

$$s_u = \frac{q_{net}}{N_{kt}} \tag{3}$$

Similarly, Δu and q_e are related to s_u by means of the cone factors $N_{\Delta u}$ and N_{ke} respectively as:

$$s_u = \frac{\Delta_u}{N_{\Delta u}} \tag{4}$$

$$s_u = \frac{q_e}{N_{ke}} \tag{5}$$

For low OCR offshore and onshore clays, Low et al. (2010) reported N_{kt} = 8.6-15.3 and $N_{\Delta u}$ = 3.3-8.8 for triaxial compression (CAUC) and N_{kt} = 11-20 and $N_{\Delta u}$ = 4.8-11.9 for field vane test (FVT). Paniagua et al. (2019) found N_{kt} = 5-16 and $N_{\Delta u}$ = 5-10 for CAUC in onshore Norwegian clays with OCR less than 6. Paniagua et al. (2019) further observed N_{ke} ≈1,5-10 for CAUC decreasing with increasing B_q. Selänpää (2021) suggested N_{kt} = 9.1, $N_{\Delta u}$ = 7.7, and N_{ke} = 4.5 with COV ≈ 0.1 for CAUC in Finnish soft lightly overconsolidated clays. D'Ignazio & Lehtonen (2021) observed $N_{\Delta u}$ ≈ 11 for FVT in a soft organic sulphate rich lightly overconsolidated clay from Finland. D'Ignazio et al. (2020) found N_{kt} = 20-32 (CAUC) for an overconsolidated North Sea clay with OCR ≈ 4-20, with N_{kt} increasing with increasing OCR.

4 HIGH-QUALITY CLAY DATABASES

4.1 *Norway*

The Norway CPTU database is presented in detail by Paniagua et al. (2019). The database consists of 61 high-quality block samples data points collected from 17 Norwegian clay sites located all over the country. For these points, both CPTU and laboratory measurements are available. The laboratory tests were carried out on specimens obtained from large diameter (Ø250 mm) block samples and mini-block (Ø150 mm) Sherbrook samples (Emdal et al. 2016). For Norwegian clays, block samples seem to ensure higher quality than the more traditional Ø54 mm or Ø72 mm piston samples (e.g., Lunne et al. 2006, L'Heureux et al. 2018).

The database includes laboratory index tests, constant-rate-of-strain (CRS) oedometer tests, anisotropically consolidated undrained triaxial compression (CAUC) and extension tests (CAUE) and direct simple shear tests (DSS).

Sample quality was assessed according to the Lunne et al. (1997b) criterion based on the normalized change in void ratio $\Delta e/e_0$ from CAUC tests. Data points fall within sample quality categories "Very good to excellent" and "Good to fair".

Soil properties were measured from specimens collected down to a maximum depth of 22 m. The clay properties cover a wide range of plasticity index, with I_p varying between 4 (low plastic) and 49 (very high plastic), a wide range of water content (w = 28–72%), a wide range of sensitivity (S_t) values (S_t = 2–240). The OCR ranges from 1 to 6, while the clay content varies between 21 and 65%.

4.2 *Finland*

The Finland TUNI's CPTU database in summarized in the works carried out by Di Buò (2019), with focus on preconsolidation stress, and Selänpää (2021), with focus on undrained shear strength. Data was collected from 5 test sites located in Southern Finland. Both CPTU and laboratory measurements are available from the test sites.

The laboratory tests were carried out on specimens obtained from large diameter (Ø132 mm) Laval-type sampled designed by Tampere University and presented in detail by Di Buò et al. (2019). Some of the tests were performed on specimens obtained from a mini-block (Ø150 mm) Sherbrook sampler (Emdal et al. 2016).

The database includes laboratory index tests, n.99 constant-rate-of-strain (CRS) oedometer tests, n. 17 anisotropically consolidated undrained triaxial compression (CAUC) and n. 14 extension tests (CAUE), n. 14 direct simple shear tests (DSS) and n. 14 field vane tests (FVT).

Sample quality was assessed according to the Lunne et al. (1997b) criterion based on the relative void ratio change at reconsolidation $\Delta e/e_0$ from CAUC as well as CRS tests. CAUC data points from Ø132 mm samples fall within sample quality categories "Very good to excellent", while the CRS data points and fall within "Very good to excellent" and "Good to fair" sample quality categories.

Soil properties were measured from specimens collected down to a maximum depth of 9 m. The clay properties cover a plasticity index I_p varying between 16 (low-medium plastic) and 59 (very high plastic), a wide range of water content (w = 66–127%), a wide range of sensitivity (S_t) values (S_t = 16–98). The OCR ranges from 1 to 2, while the clay content varies between 40 and 100%.

5 COMPARISON OF CPTU DATABASES OF NORWEGIAN AND FINNISH CLAYS

5.1 *Overconsolidation ratio*

Figures 1, 2 and 3 show plots of OCR versus the normalized values of cone resistance Q_t, pore pressure Q_u and effective cone resistance Q_e. The plots suggest a well-defined trend line for the Finland data, while the Norway data appears to be characterized by higher scatter.

Even though the uncertainty associated with OCR for Finnish clays appears to be lower than that for the Norwegian clays, it must be noted that the Finland data is obtained from 5 sites all located in the Southern part of the country; while the Norwegian data is collected from 17 sites spread all over the country, where areas might have undergone different geological histories. However, the OCR range of the Finland data (OCR = 1-2) is lower than that of the Norway data (OCR = 1-7). For OCR < 2, the mean trends of the two databases appear to be consistent, despite the larger scatter in the Norway data. Consistency is also found between the OCR based on mini-block samples and Ø132 mm samples of Finnish soft clays.

The coefficient k of Equation 2 is ≈0.3 in Figure 1 for Finnish clays. Such a value is often assumed in practice in absence of site-specific oedometer tests.

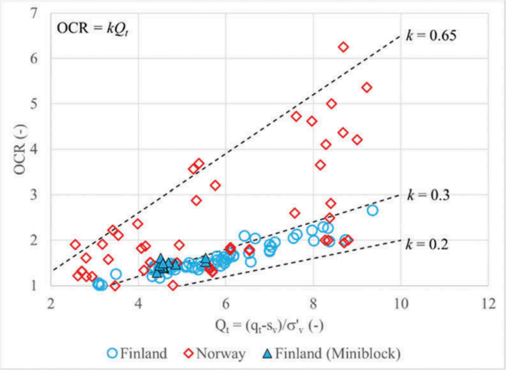

Figure 1. OCR vs Q_t.

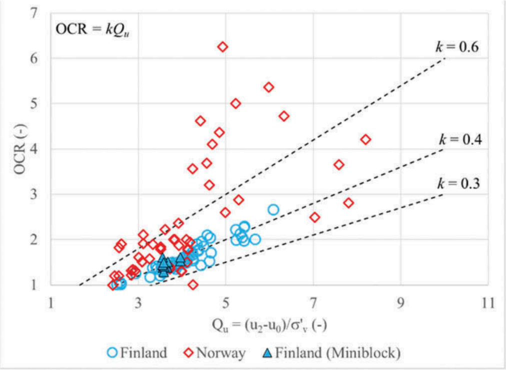

Figure 2. OCR vs Q_u.

Data in Figures 1, 2 and 3 show a remarkable variability of the calibration coefficients, particularly for the Norwegian database. Figure 4 shows the variation of k (=OCR/Q_t) with plasticity index (I_p). The coefficient k appears to vary as a function of plasticity, decreasing with increasing I_p. Such a trend could not be observed when treating the two databases separately. Nevertheless, for I_p < 20%, the data from Finland is consistent with measurements at larger I_p.

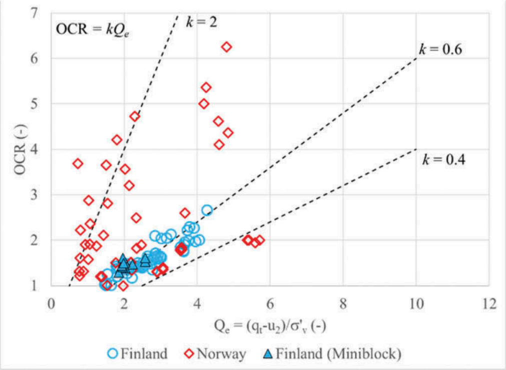

Figure 3. OCR vs Q_e.

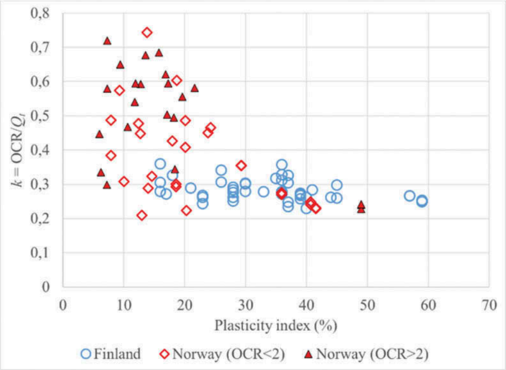

Figure 4. K = OCR/Q_t vs plasticity index.

5.2 *Undrained shear strength*

The undrained shear strength from triaxial CAUC tests (s_{uC}) is taken as a reference and used for comparison of the Finland and Norway databases.

Figures 5, 6 and 7 illustrate the variation of s_{uC} with q_{net}, Δu and q_e respectively. The s_{uC} from Finnish clay deposits is generally lower than that of Norwegian clays. It must be noted that the sampling depths are limited to 9 m below ground level for the Finland data, while depths reach up to 22 m for the Norway data. Therefore, the deeper samples in the Norway database experienced larger stress relief than the samples from Finland. Nevertheless, for the depth range 0-9 m, s_{uC} of Norwegian clays is in the range 26-62 kPa, while s_{uC} of Finnish clays is 12-24 kPa. One possible explanation for this is the variation of OCR with depth. As shown in Figure 8, the range of OCR is larger for the Norwegian data. Given that s_u increases with increasing OCR (e.g. D'Ignazio et al. 2016, Selänpää 2021), this explains the higher strength of Norwegian clays at shallow depths.

The cone factor values for Norwegian and Finnish clays are discussed in detail by Paniagua et al. (2019)

and Selänpää (2021). Cone factors N_{kt}, $N_{\Delta u}$ and N_{ke} present some variability as illustrated in Figures 5, 6 and 7. As for the OCR, the variability appears to be the lowest for the Finland data. The variability of cone factors for Norwegian clays was discussed by Karlsrud et al. (2005) and Paniagua et al. (2019). These studies suggested a dependency of cone factors on OCR and lightly on index properties, although the proposed correlations are characterized by a non-negligible scatter.

Figure 9 presents the variation of the normalized CAUC strength s_{uC}/σ'_v with OCR. In agreement with previous analyses, the Finland data shows overall a well-defined trend and a lower scatter. For OCR < 2, the normalized s_{uC}/σ'_v of Finnish clays appears to be higher than that of the Norwegian clays, with the Miniblock samples data from Finland showing slightly higher values than the Laval Ø132 mm samples. This may result from the fact that the lower OCR points in the Norway database are observed at greater depths than in the Finnish database (Figure 8). This may be an indicator of the stress dependency of the normalized shear strength of clays.

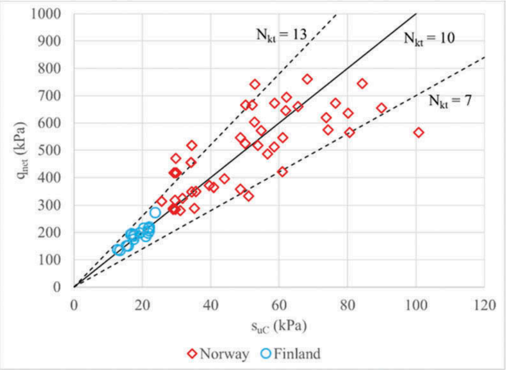

Figure 5. Q_{qnet} vs s_{uC}.

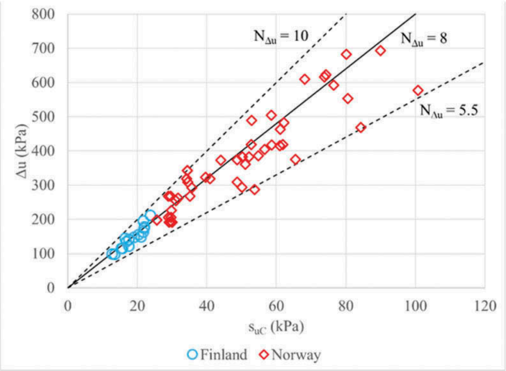

Figure 6. Δu vs s_{uC}.

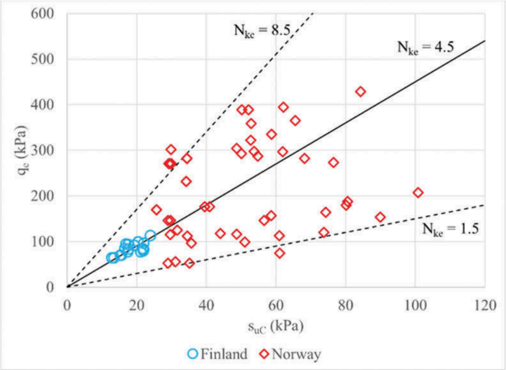

Figure 7. Q_e vs s_{uC}.

Karlsrud & Hernandez-Martinez (2013) and Paniagua et al. (2019) discussed how the variability of Norwegian clays in Figure 9 may be captured by the variability of water content. Considering that the Finland data is characterized by higher water content, this may further support the results of these studies.

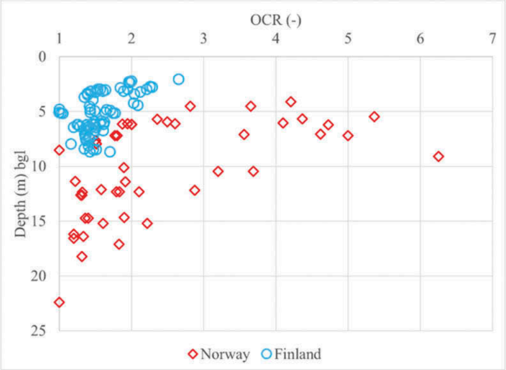

Figure 8. OCR vs depth.

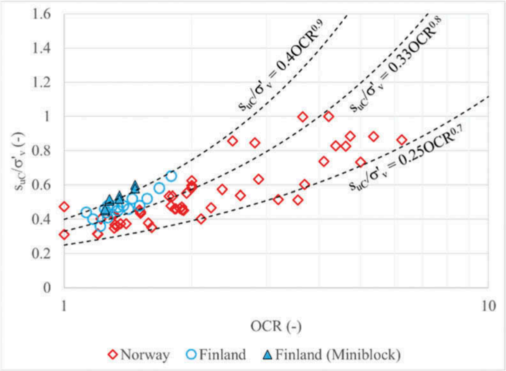

Figure 9. s_{uC} vs OCR.

6 DISCUSSION AND CONCLUSIONS

This study has compared two high-quality clay databases from Finland and Norway. Both databases include piezocone (CPTU) measurements and laboratory testing from different sites. Laboratory specimens were mainly retrieved from large diameter block sampler (Norway) and large diameter Laval-type tube sampler (Finland). Constant-rate-of-strain (CRS) oedometer tests results and undrained triaxial compression (CAUC) tests were used as reference tests to compare the overconsolidation ratio (OCR) and undrained shear strength from triaxial compression tests (s_{uC}) and their trends with respect to CPTU parameters.

The study showed that the shear strength of Finnish clays is lower than that of Norwegian clays. This is mainly due to the stress histories of the soils, i.e., the OCR of Finnish clays is generally lower when comparing samples from the same depth interval.

The larger scatter in both OCR and s_{uC} observed for the Norwegian data might be related to the fact that the Finnish data is collected from 5 sites all located in Southern Finland, while the Norwegian database comprises 17 sites spread all over Norway, where areas might have experienced different depositional histories and relative fall of sea level. Furthermore, the Finnish data has been collected using the same piezocone and sampling equipment for all sites, while the Norwegian data has been acquired over a period of 30+ years using different equipment. Even though data has been collected according to best practice, differences in measured CPTU parameters may be observed when using different cones (Lunne et al. 2018).

Future research shall focus on the mineralogy of clays. Mineral composition can have a large effect on the flocculation potential and building of strength of the soil (e.g. Torrance 2014). Depositional and post-depositional processes for both countries are also important aspects to investigate in depth. For a more thorough comparison, it is recommended to add data from Central and Northern Finland to the Finnish database.

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