REPORT

SP8 - Soil Parameters in Geotechnical Design (GEODIP)

CPTU CORRELATIONS FOR CLAYS

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Summary

As part of the R&D project GEODIP-SP8, a multivariate high-quality database of sensitive clays consisting of laboratory strength and consolidation test results, index parameters and CPTU parameters was established. The present report evaluates, with the help of multiple regression analyses, possible correlations among measured CPTU parameters (e.g. excess pore pressure, Δu, net cone resistance, q_{net}, and effective cone resistance, q_e), undrained shear strength from CAUC tests (s_u^C) and some basic clay properties (e.g., OCR, plasticity) included in the database.

The first part of the report presents the collected data points and it discusses sample quality. Then, correlations based on simple and multivariable linear regression analyses are proposed for undrained shear strength, overconsolidation ratio and preconsolidation stress. The goodness of the established correlations established is checked for seven test sites in Norway. Finally, recommendations for engineering practice are given based on the outcomes of this study.

Contents

Appendix

Review and reference page

1 Introduction

1.1 Background

All building and construction works require reliable and proper selection of geotechnical design parameters. A thoughtful choice of the most appropriate investigation method is likely to result in improved understanding of soil behaviour and, therefore, in more cost-effective and sustainable solutions for the construction, transport and energy sectors. The geotechnical community in Norway and abroad agrees that there is a need for better understanding of the behaviour of sensitive clays in order to improve geotechnical design practice, with the scope of making it more innovative, and to reduce risks related to the occurrence of more or less catastrophic events (e.g. landslides, excavation failure).

NGI has carried out several studies on characterization of sensitive clays and on effect of sample quality on the choice of geotechnical design parameters. In particular, the use of high-quality block samples (Ø250mm) over the more traditional Ø54mm or Ø72mm seemed to ensure better sample quality (e.g. Lunne et al. 1997; Lunne et al. 2006; Karlsrud and Hernandez-Martinez 2013), which is mainly reflected in the higher measured undrained shear strength (s_u), higher inferred preconsolidation pressure (p'_c) and higher measured soil stiffness (both drained and undrained).

Geotechnical design in sensitive clay areas in Norway is mainly based on piezocone (CPTU) test results. CPTU parameters are usually derived based on empirical correlations against parameters established through soil sampling and laboratory testing. For instance, cone factors for undrained shear strength (N_{kt}, $N_{\Delta u}$, N_{ke}) can be correlated with OCR, plasticity and/or sensitivity (Karlsrud et al., 2005). The quality of the empirical correlations is directly linked to the quality of the tests used to calibrate such models. Besides NGI's decades of experience, examples of how the use of high-quality samples resulted in improved and more cost-effective CPTU-based design are also presented in the literature (e.g., Lunne and Powell, 2007; Robertson et al., 2009; L'Heureux et al. 2018).

To follow up on this the NGI funded the strategic R&D project SP8-GEODIP. The work presented in this report constitutes part of the SP8-GEODIP project and it focuses on the determination of correlations for CPTU parameters based on block samples data of sensitive clays.

1.2 Objectives and scope of work

One of the main activity of the SP8 project has been to establish a multivariate high-quality database of sensitive clays consisting of laboratory strength and consolidation test results, index parameters and CPTU parameters. A full overview of the database is presented in NGI report 20150030-02-R and the database can be found as an Excel file on the following path:

P:\2015\00\20150030\DP-1-Database_work\High-quality-database-clay-APP

The aim of this report is to evaluate, with the help of multiple regression analyses, possible correlations among measured CPTU parameters (e.g. excess pore pressure, Δu, net cone resistance, q_{net}, and effective cone resistance, q_e), undrained shear strength from CAUC tests (s_u^C) and some basic clay properties (e.g., OCR, plasticity).

The first part of the report presents the collected data points and it discusses sample quality. Then, correlations based on simple and multivariable linear regression analyses are proposed for undrained shear strength, overconsolidation ratio and preconsolidation stress. The goodness of the established correlations established is checked for seven test sites in Norway. Finally, recommendations for engineering practice are given based on the outcomes of this study.

2 Effects of sampling method and block sampling

Sample disturbance may occur during drilling, sampling, transportation, storage or preparation for testing. Any sample of soil being taken from the ground, transferred to the laboratory and prepared for testing will be subject to disturbance. The mechanisms associated with the disturbance may be classified as follows (Clayton et al. 1982):

1. Changes in stress conditions
2. Mechanical deformation
3. Changes in water content and void ratio
4. Chemical changes

A reduction in total stresses will inevitably occur at some point during the sampling process. For instance, making a borehole reduces the total stresses at its base, using sampling tubes with inside clearance reduces the lateral total stresses and extrusion of the soil specimen will usually bring the total stresses in all directions to zero.

The choice of sampling method strongly influences the sample quality (Berre et al. 2007; Lunne et al. 2006; Lunne and Andersen 2007). Each sampling method trigger different mechanisms leading to sample disturbance as classified above. For the purpose of this study, only data obtained using the Sherbrooke block sampler (Lefebvre and Poulin 1979) are considered.

The Sherbrooke block sampler was developed and tested at Sherbrooke University, Quebec, Canada during the period 1975-1978 (Lefebvre and Poulin 1979). This sampler allows carving of cylindrical blocks with diameter and height of 250 mm and 350 mm respectively. Karlsrud et al., (2012) describes the practical aspects of block sampling.

Block sampling is an excellent method of ensuring that the soil remains unaffected by shear distortions during sampling, but samples obtained in this way may not, due to swelling, have the same effective stresses as those in the ground. This should be accounted for using appropriate reconsolidation procedures. The NGI believes this sampler gives the highest quality samples available (Lunne et al. 2006).

3 CPTU database of sensitive clays

3.1 Basic parameters

The database consists of 61 block samples data points collected from 17 sites from Norway and the well-investigated Bothkennar soft clay site from UK. Some of the data have been already presented in Karlsrud et al. (2005) and Karlsrud and Hernandez-Martinez (2013) and exploited to derive correlations for anisotropic strength and stiffness of sensitive clays and CPTU correlations. More recent block samples data from the soil investigation for the construction of the new highway E16, from Nybakk to Slomarka, are also included (NGI report 20150030-08-R), in addition to block samples collected at Skatval and Koa in Trøndelag. For more information and updates about NGIs block samples database the reader is referred to NGI reports 20150030–02–R and 20150030–08–R.

Some of the parameters contained in the database are:

- **q_t**: corrected cone tip resistance
- **q_{net}**: net cone tip resistance, $q_t - p_0$, where p_0 is the total overburden stress
- **u_2**: pore pressure measured during cone penetration
- **Δu**: $u_2 - u_0$, where u_0 is the hydrostatic pore pressure
- **s_u^C**: peak undrained shear strength from anisotropically consolidated triaxial compression (CAUC) tests. Tested specimen were reconsolidated to the in-situ stress state.
- **p'_c**: inferred preconsolidation stress from constant-rate-of-strain (CRS). Values are interpreted according to Karlsrud (1991) and Karlsrud and Hernandez-Martinez (2013). Janbu (1969) method was also used for p'_c interpretation control.
- **p'_0**: in-situ vertical effective stress
- **OCR**: overconsolidation ratio, $= p'_c/p'_0$
- ***w***: natural water content
- **PI**: plasticity index
- **S_t**: sensitivity measured from Fall Cone test
- **Clay content**

The basic statistics of the abovementioned soil parameters are summarized in Table 3.1.

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 PI 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 6.25, while the clay content varies between 21 and 64.5%.

Table 3.1 Statistics of the basic parameters in the database

Variable	**n**	**Mean**	**COV**	**Min**	**Max**
q_t (kPa)	61	644.80	0.32	220	1115
q_{net} (kPa)	61	469.51	0.32	169	760.3
u_2 (kPa)	61	442.70	0.36	150	788
Δu (kPa)	61	362.68	0.38	122	693.3
s_u^C (kPa)	61	47.50	0.41	15.3	100.8
p'_c (kPa)	61	209.80	0.55	47.46	475
p'_0 (kPa)	61	96.15	0.54	22.6	227
OCR	61	2.40	0.52	1	6.25
w (%)	61	42.58	0.31	27.9	72.2
PI (%)	61	19.83	0.61	4	49
S_t	59	37.96	1.59	2	240
Clay content (%)	56	40.93	0.25	21	64.5

3.2 Evaluation of sample disturbance

Evaluation of sample disturbance is an important task in geotechnical engineering and the topic has been given much attention. This has led to several criteria for assessment of sample quality (e.g. Lunne et al. 1997; Donohue and Long 2007; Karlsrud and Hernandez-Martinez 2013). In this work, the change in void ratio relative to the initial void ratio, $\Delta e/e_0$, is used to evaluate sample disturbance according to NGF publication no. 11 (NGF 2013) (Table 3.2).

Table 3.2 Criteria for sample quality after NGF (Norwegian Geotechnical Society, 2013)

OCR	**$\Delta e/e_0$**			
1-2	<0.04	0.04-0.070	0.070 - 0.140	> 0.14
2-4	<0.03	0.03-0.050	0.050 - 0.100	> 0.10
4-6	<0.02	0.02-0.035	0.035 – 0.070	> 0.07
Quality	1: Very good to excellent	2: Good to fair	3: Poor	4: Very poor

Figure 3.1 illustrates the normalized change in void ratio from CAUC tests on samples from the different test sites. It is evident that the normalized change in void ratio tends to increase with increasing depth for all samples. This tendency has also been observed by Amundsen et al. (2016) for low plasticity clays. Despite the increasing $\Delta e/e_0$ with depth, data points fall within sample quality categories 1 and 2 (Table 3.2), as shown in Figure 3.2 (which also takes OCR into account). Therefore, the collected data points are considered of high-quality.

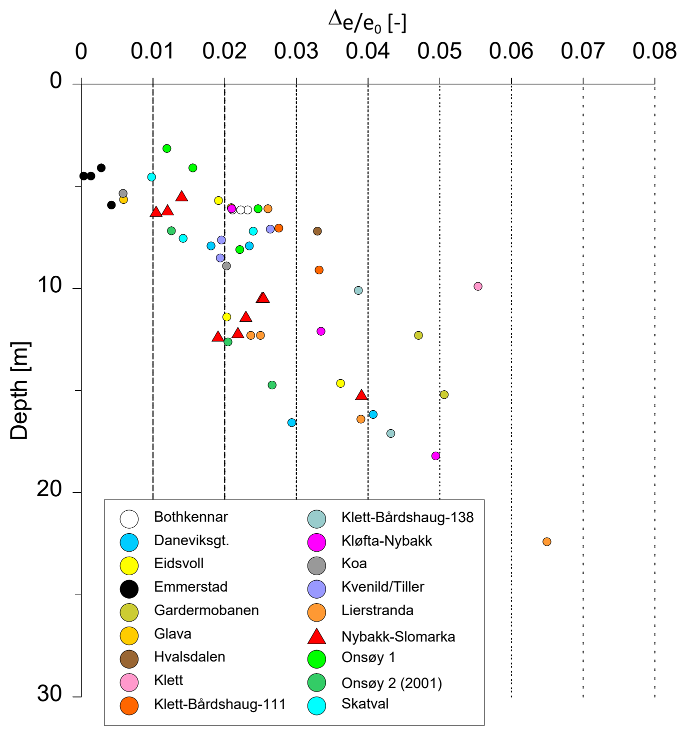

Figure 3.1 Normalized change in void ratio ($\Delta e/e_0$) from CAUC tests on block samples versus depth for different sites.

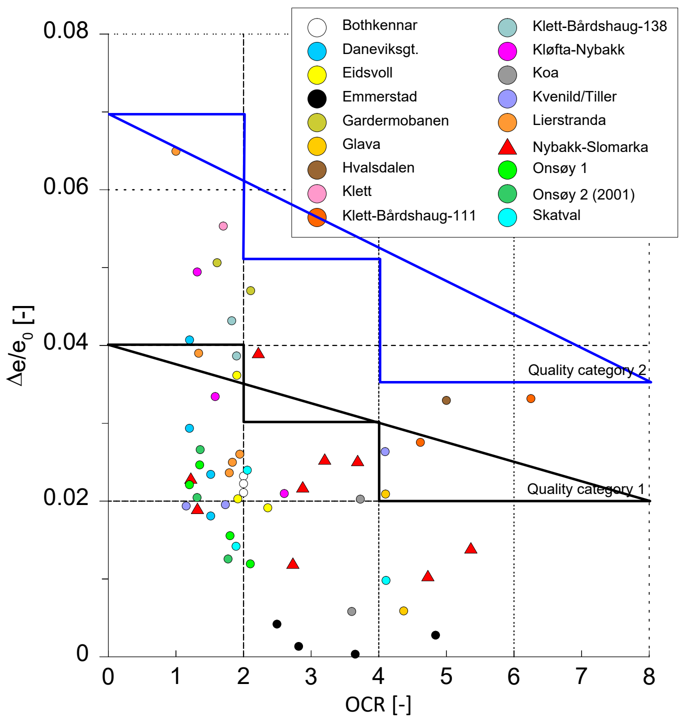

Figure 3.2 Normalized change in void ratio ($\Delta e/e_0$) from CAUC tests versus over-consolidation ratio OCR for different sites.

4 CPTU results and correlations

4.1 Definition of CPTU factors considered

Measured cone tip resistance (q_t) and excess pore pressure (Δu or u_2) are the most frequently used parameters in CPTU correlations for undrained shear strength (e.g. Karlsrud et al. 2005). Different cone factors are used to correlate the measured parameters to the laboratory undrained shear strength. In the international literature, the reference undrained shear strength is sometimes measured in other tests than CAUC (e.g., field vane test, DSS). At NGI, s_u^C has been used as reference for over 25 years.

The corrected cone tip resistance q_t is related to CAUC traxial undrained shear strength (s_u^C) by means of the cone factor N_{kt}, as:

$$N_{kt} = \frac{q_t - p_0}{s_u^C} = \frac{q_{net}}{s_u^C}$$

The measured excess pore pressure is related to s_u^C by means of the cone factor $N_{\Delta u}$, as:

$$N_{\Delta u} = \frac{u_2 - u_0}{s_u^C} = \frac{\Delta u}{s_u^C}$$

The combination of cone resistance and excess pore pressure can be also related to s_u^C by means of the cone factor N_{ke}, as:

$$N_{ke} = \frac{q_t - u_2}{s_u^C}$$

Other commonly used factors for CPTU correlations are the pore pressure factor, B_q, and the normalized net cone resistance, Q_t. These parameters are defined as:

$$B_q = \frac{u_2 - u_0}{q_t - p_0}$$

$$Q_t = \frac{q_t - p_0}{p'_0} = \frac{q_{net}}{p'_0}$$

Several authors have proposed relationships between cone factors and soil parameters. For instance, Karlsrud et al. (2005) established CPTU correlations for undrained shear strength of Norwegian clays. Karlsrud et al. (2005) grouped cone factors based on S_t: S_t<15 and S_t>15. N_{kt} was observed to increase with increasing OCR and, for S_t>15, also with PI. $N_{\Delta u}$ was, on contrary, observed to decrease with increasing OCR. N_{ke} was reported to linearly decrease with increasing B_q.

For normally to slightly overconsolidated clays from Sweden, Larsson et al. (2007) suggested N_{kt} to increase with increasing liquid limit and $N_{\Delta u}$ to decrease with decreasing liquid limit.

Low et al. (2010) attempted to correlate, based on a database of onshore as well as offshore clays from different sites around the world, cone factors to soil parameters such as PI, S_t, strength anisotropy and rigidity index, I_r (G_{50}/s_u^C). No clear correlations for cone factors could be observed.

4.2 Undrained shear strength correlations

Figure 4.1 and Figure 4.2 show the net cone resistance (q_{net}) and the excess pore pressure ($\Delta u = u_2 - u_0$) against the measured undrained shear strength from triaxial compression tests (s_u^C). Based on these figures, the measured s_u^C seems to better correlate with Δu than with q_{net} (lower scatter and, therefore, higher coefficient of determination, r^2).

CPTU correlations for Norwegian clays have previously been established by Karlsrud et al. (2005); both for the overconsolidation ratio (OCR) and for estimation of undrained shear strength.

In Figure 4.3, the measured cone factor N_{kt} is compared to the correlations by Karlsrud et al. (2005) for N_{kt} as a function of OCR and sensitivity. The data points show high scatter and it seems difficult to identify a reasonable statistical trend between N_{kt} and OCR.

Similar considerations can be done by looking at the relationship between $N_{\Delta u}$ and OCR (Figure 4.4). Even though the suggested regression line shows $N_{\Delta u}$ decreasing with increasing OCR, in agreement with Karlsrud et al.'s (2005) correlations trend, the calculated coefficient of determination (r^2) is rather low.

A fairly good agreement is found between N_{ke} and the B_q parameter, as shown in Figure 4.5. The calculated regression line agrees with the Karlsrud et al.'s (2005) relations, accompanied by $r^2 = 0.81$, which is considerably higher than r^2 in Figure 4.3 and Figure 4.4. However, this approach must be carefully used, as N_{ke} is very sensitive to small changes in B_q.

Correlations between N_{kt}, $N_{\Delta u}$ and B_q are not presented, since, as pointed by Karlsrud et al. (2005), these would only be representative of how the measured excess pore pressure vary with undrained shear strength.

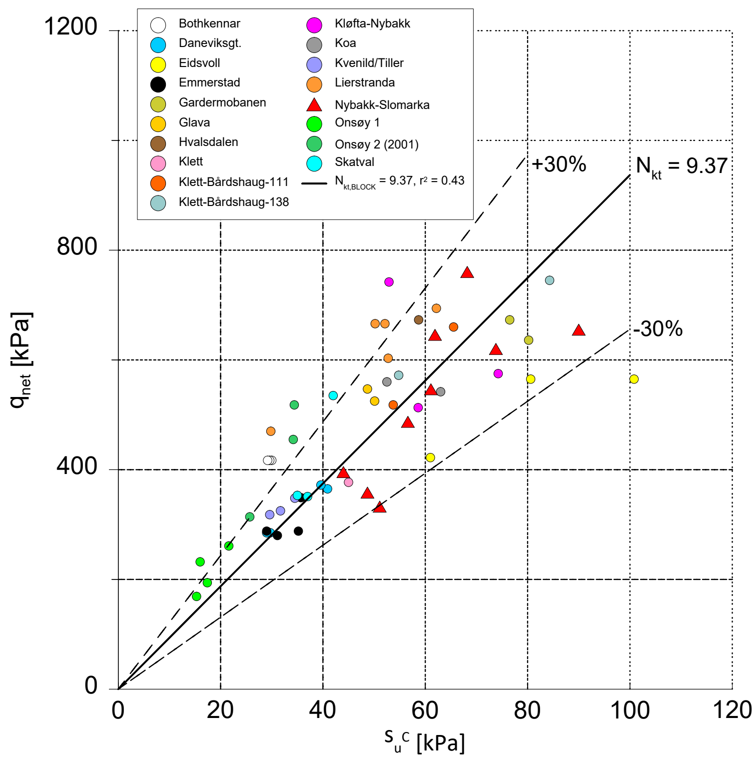

Figure 4.1 Net cone resistance (q_{net}) against CAUC undrained shear strength s_u^C.

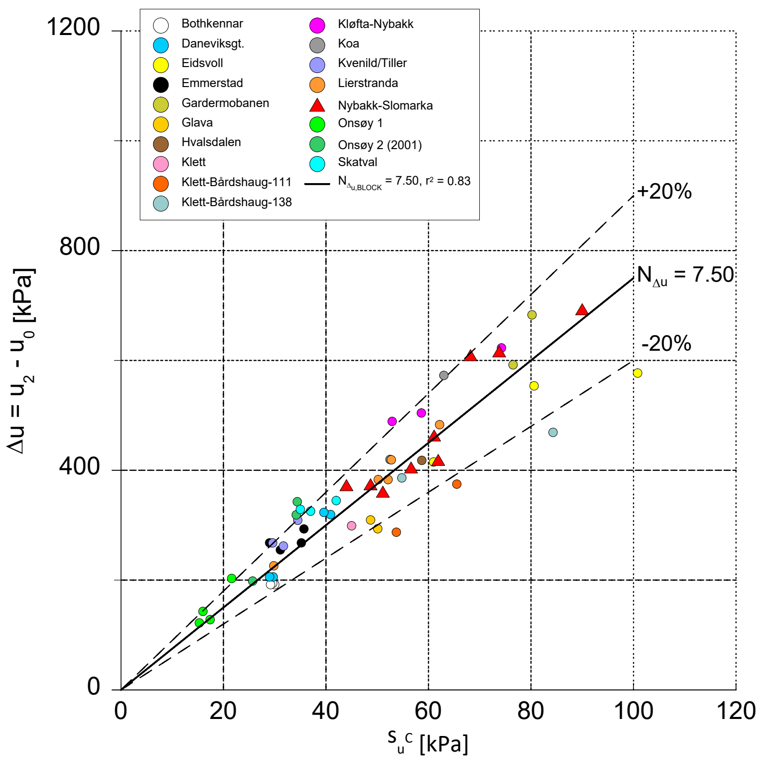

Figure 4.2 Excess pore pressure (Δu) against CAUC undrained shear strength s_u^C.

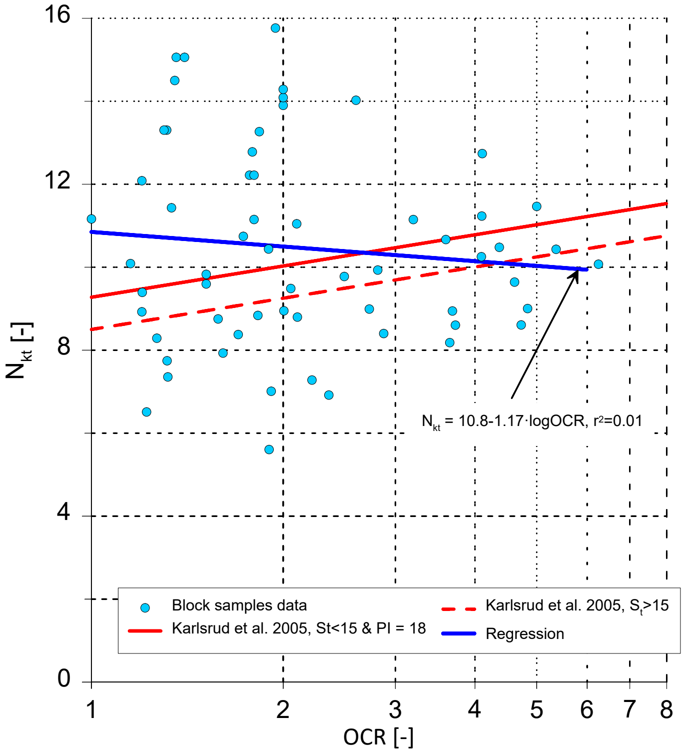

Figure 4.3 N_{kt} against overconsolidation ratio, OCR.

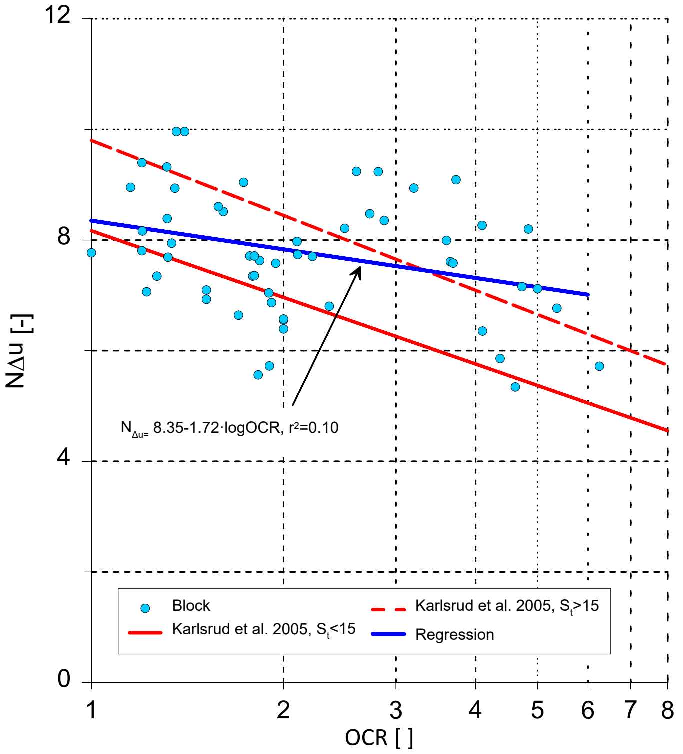

Figure 4.4 $N_{\Delta u}$ against overconsolidation ratio, OCR.

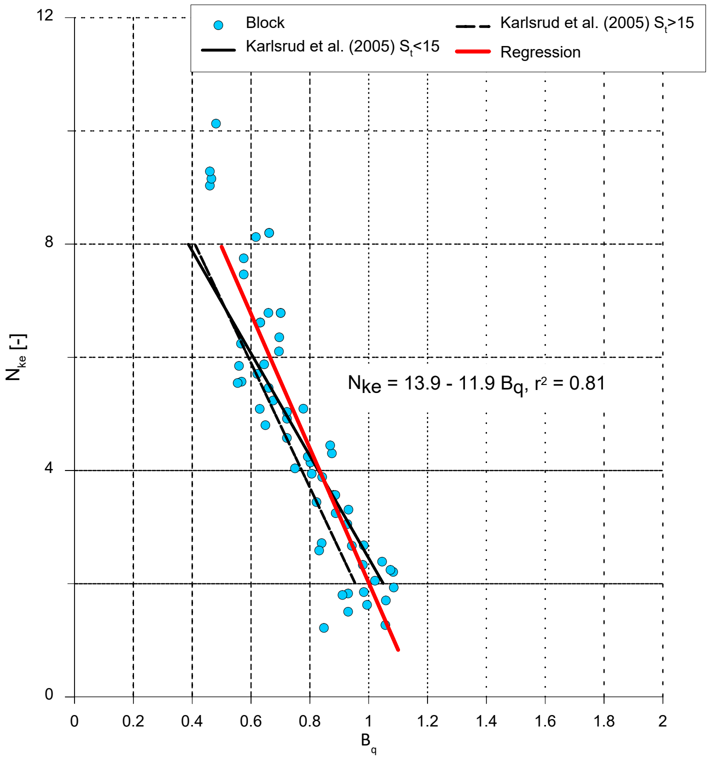

Figure 4.5 N_{ke} against B_q.

Figure 4.6 suggests N_{kt} increasing with increasing plasticity index, PI. Even though the trend seems fairly well defined, the regression line is characterized by a low r^2. On the other hand, it is not possible to observe a marked dependency of the cone factor $N_{\Delta u}$ on PI, as shown by Figure 4.7. Despite the relatively high scatter observed, a linear dependency seems to exist also between N_{ke} and PI, increasing with increasing PI (Figure 4.8). The calculated r^2 is similar to the r^2 between N_{kt} and PI.

Karlsrud et al. (1995) mentioned that the plasticity index of clays is influenced by the sensitivity: normally or lightly over consolidated leached clays with high sensitivity will in un-leached state have a plasticity index which is typically a factor of 1.5 to 2.0 larger than the leached high sensitive clay. Therefore, IP is a parameter that can be misleading for clays (Karlsrud and Hernandez-Martinez, 2013) with high sensitivity since the liquid limit might decrease significantly for sensitive clays. However, in the updated database values around IP = 18 and w_L = 38% were observed for both non-sensitive and sensitive clays. In any case, IP affects the r^2 of equation [4] by not more than 3%.

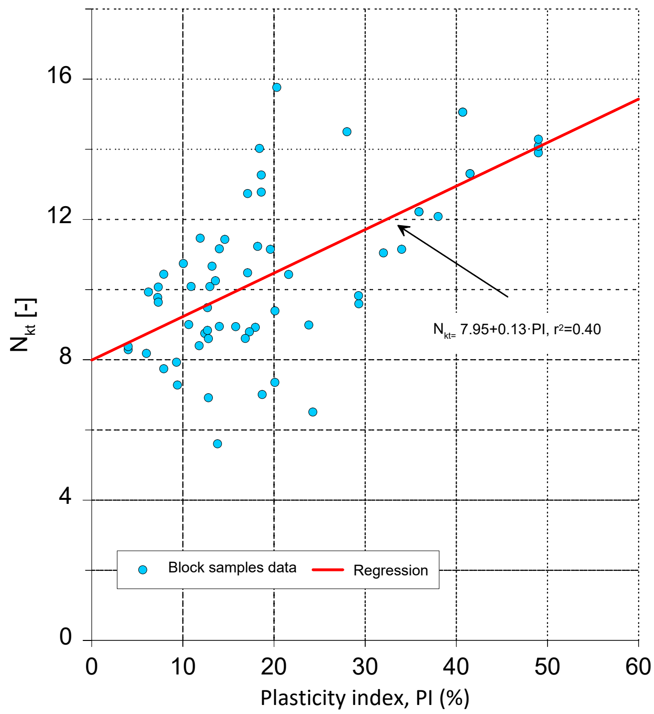

Figure 4.6 N_{kt} against plasticity index, PI.

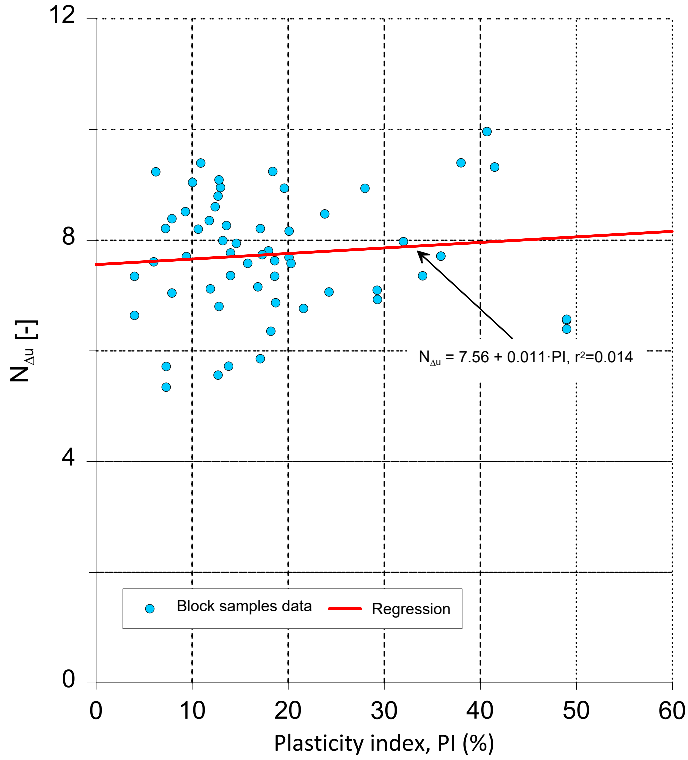

Figure 4.7 $N_{\Delta u}$ against plasticity index, PI.

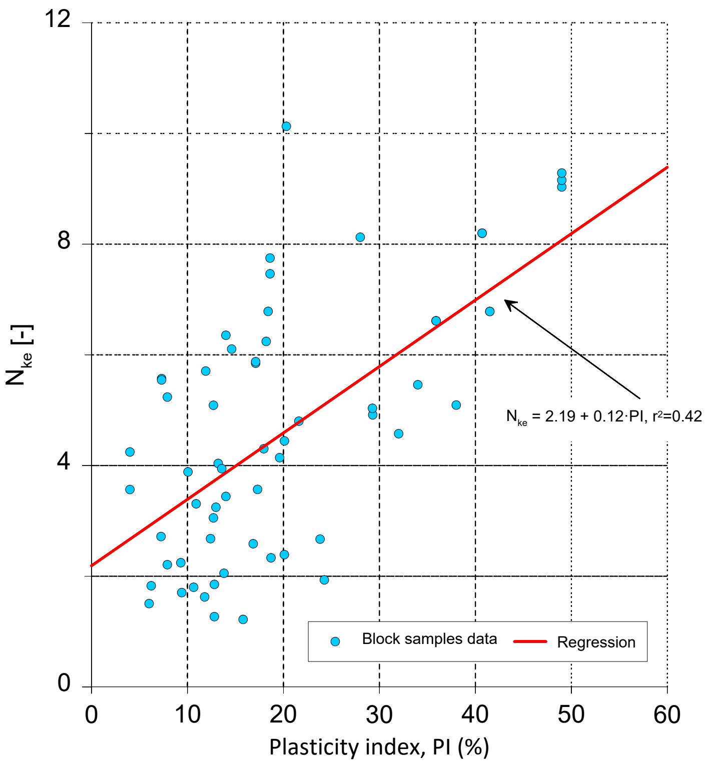

Figure 4.8 N_{ke} against PI.

The dependency of cone factors on sensitivity (S_t) was discussed in Karlsrud et al. (2005). Karlsrud et al. (2005) and Karlsrud and Hernandez-Martinez (2013) proposed a boundary between low sensitive and high sensitive clays at $S_t = 15$.

No marked dependency could be observed between $N_{\Delta u}$ or N_{ke} on S_t. Therefore, these relations are not shown in this report. On the other hand, N_{kt} seems to show a dependency on S_t for $S_t > 30$, as shown in Figure 4.9. For high sensitive to quick clays, N_{kt} appears to linearly decrease with increasing S_t.

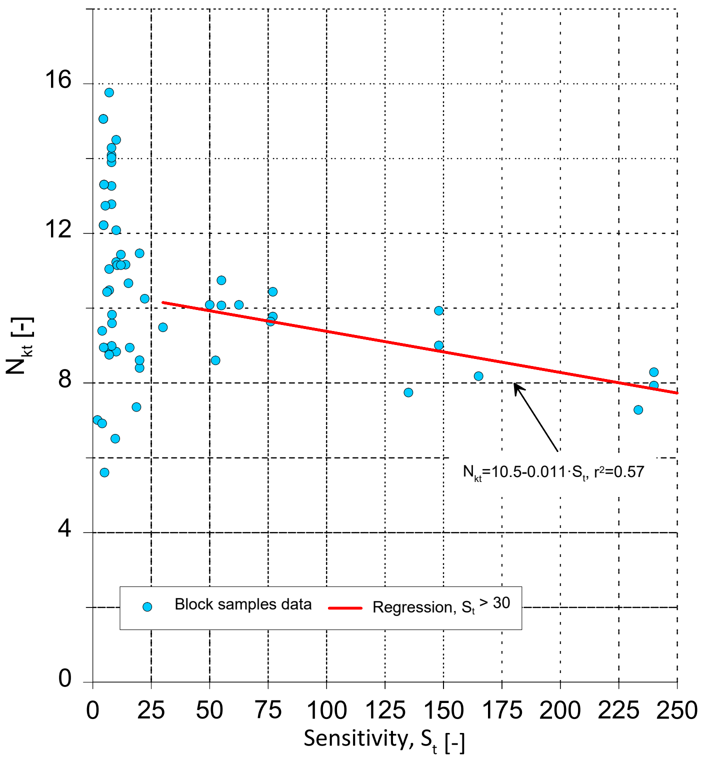

Figure 4.9 N_{kt} against sensitivity, S_t.

In order to obtain improved expressions for cone factors of sensitive clays, multivariable linear regression analyses were performed to evaluate the interdependence of N_{kt}, $N_{\Delta u}$, N_{ke} and clay parameters (e.g. OCR, PI, S_t…) to maximize the r^2 of the correlations. Only the equations showing the best fit, in terms of calculated r^2, to the database are presented in this report.

For N_{kt}, the multivariable regression analysis did not show any remarkable improvement in the calculated r^2. The highest r^2 were measured for equations [1] and [2], suggesting a linear dependency between N_{kt} and PI and N_{kt} and S_t (only for $S_t > 30$).

[1] $N_{kt} = 7.95 + 0.13 \cdot PI$ $r^2 = 0.40$

[2] $N_{kt} = 10.5 - 0.011 \cdot S_t$ $r^2 = 0.57$, for $S_t > 30$

No clear dependency could be observed between $N_{\Delta u}$ and the basic clay parameters included in the database. The linear regression analyses indicated $N_{\Delta u}$ constant and equal to 7.50 (equation [3]) to give the highest $r^2 = 0.83$. This is remarkably higher than the r^2 for N_{kt} from equations [1] and [2].

[3] $N_{\Delta u} = 7.50$ $r^2 = 0.83$

Unlike N_{kt} and $N_{\Delta u}$, N_{ke} seems to correlate with different parameters. As shown in equation [4], N_{ke} can be linearly correlated to B_q, OCR and PI. The multivariable regression analysis resulted in a notably higher calculated r^2 than in Figure 4.8.

[4] $N_{ke} = 14.3 - 12.1 \cdot B_q - 2.6 \cdot log\,OCR + 0.027 \cdot PI$ for $Bq < 1.0$ $r^2 = 0.91$
$N_{ke} = 6.4 - 3.3 \cdot B_q - 2.6 \cdot log\,OCR - 0.015 \cdot PI$ for $Bq \geq 1.0$ $r^2 = 0.82$

A multivariable regression analysis was also performed directly between undrained shear strength results from CAUC tests as a function of q_{net}, Δu and the natural water content, *w* (equation [5]). Results show a strong linear trend with r^2 close to unity.

[5] $s_u^C = 0.10 \cdot q_{net}^{0.26} \cdot \Delta u^{0.74} \cdot w^{-0.26}$ $r^2 = 0.91$

4.3 Correlations based on the SHANSEP framework

Karlsrud and Hernandez-Martinez (2013) proposed correlations for anisotropic undrained shear strength of Norwegian clays based on the SHANSEP framework (Ladd and Foott 1974) and engineering judgement. In particular, they observed a dependency between the normalized undrained shear strength (s_u^C/p'_0), the OCR and the natural water content.

For the database presented in this work, the following best fit equation was found:

[6] $\frac{s_u^C}{p'_0} = S \cdot OCR^m = 0.32 \cdot OCR^{(0.20+1.17 \cdot w)}$ $r^2 = 0.80$

Given that $s_u^C = q_{net}/N_{kt}$ or $s_u^C=\Delta u/N_{\Delta u}$, one can substitute these definitions into equation [6] and obtain equations [7] and [8]:

[7] $N_{kt} = \frac{q_{net}}{p'_0} \cdot \frac{1}{S \cdot OCR^m} = \frac{Q_t}{S \cdot OCR^m} = \frac{Q_t}{0.32 \cdot OCR^{(0.20+1.17 \cdot w)}}$

[8] $N_{\Delta u} = \frac{\Delta u}{p'_0} \cdot \frac{1}{S \cdot OCR^m}$

Equations [7] and [8] would, at first glance, indicate that N_{kt}, $N_{\Delta u}$ are inversely proportional to OCR. This would theoretically contradict what Karlsrud et al. (2005) proposed for N_{kt}, where N_{kt} increases with increasing OCR. However, the high measured Q_t in OC soils is likely to result in higher N_{kt} at high OCR values. The theoretical trend suggested by equation [8] agrees with what proposed by Karlsrud et al. (2005).

It is recommended the application of Karlsrud (1991) and/or Janbu (1969) methods for p_c' and OCR determination.

Figure 4.10 shows a comparison between measured and calculated N_{kt} values from equation [7], based on Q_t, OCR (determined by either Karlsrud (1991) or Janbu (1969) methods) and *w*. Measured and calculated data points agree relatively well. This is an expected result considering that i) the q_{net} values in the database appear on both the measured and the calculated N_{kt} and ii) some of the data points contained in the database were already exploited by Karlsrud and Hernandez-Martinez (2013) to derive equation [6].

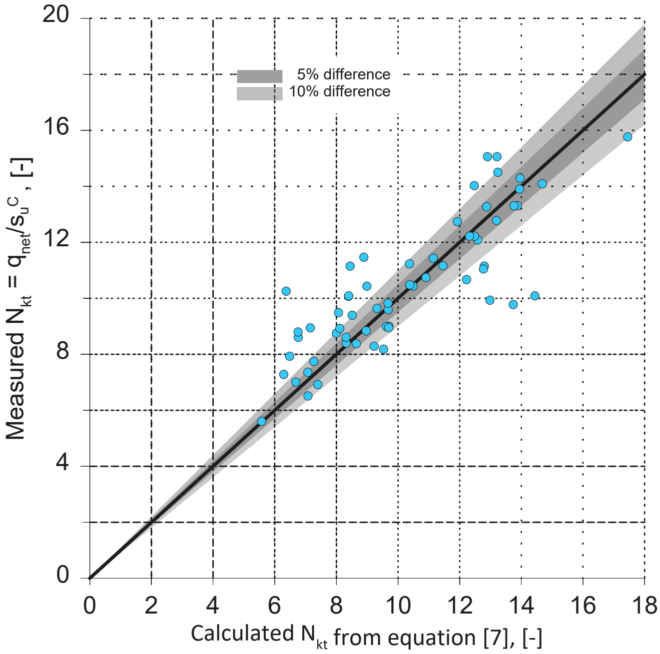

Figure 4.10 Measured N_{kt} against calculated N_{kt} from equation [6].

4.4 Preconsolidation stress and over-consolidation ratio

Another fundamental parameter for engineering practice is the preconsolidation stress (p'_c). This parameter is used to derive the overconsolidation ratio, OCR, which is used both for settlement calculations and to estimate undrained shear strength.

Leroueil et al. (1995) proposed for Canadian clays an empirical correlation between p'_c and q_{net} as:

[9] $p'_c = q_{net}/3.6$

As shown in Figure 4.11, Leroueil et al.'s (1995) correlation seems representative of the lower boundary of the measured data points. An updated relation between p'_c and q_{net} for Norwegian clays is proposed as:

[10] $$p'_c = 0.04 \cdot q_{net}^{1.37} \qquad r^2 = 0.66$$

Data points in Figure 4.11 show a high scatter. This may suggest that p'_c may depend also on other properties besides q_{net}. Hence, multivariable linear regression was carried out and the relation shown by equation [11] was obtained. A notable gain in r^2 could be obtained with respect to equation [10] by including Δu and w.

[11] $$p'_c = 2.18 \cdot q_{net}^{0.61} \cdot \Delta u^{0.54} \cdot w^{-0.65} \qquad r^2 = 0.83$$

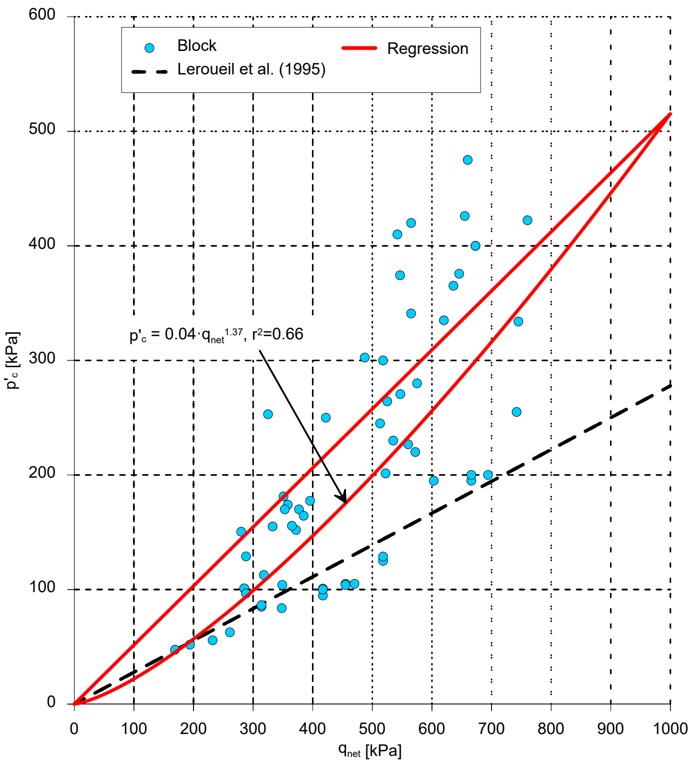

Figure 4.11 Preconsolidation pressure p'_c against q_{net}.

A relationship between OCR and Q_t was previously proposed by Mayne (1986) as follow:

[12] $$OCR = k \cdot Q_t$$

Where an average value of $k = 0.33$ was recommended by Mayne (2005) for $\varphi = 30^{o}$ and rigidity index $I_r = 100$, with a range of 0.2-0.5.

Karlsrud et al. (2005) also suggested the following relationship to evaluate OCR from CPTU test:

[13] $$OCR = \left(\frac{Q_t}{a}\right)^b$$

Where a = 3, b = 1.2 for S_t<15 and a = 2, b = 1.11 for S_t > 15.

Results from the high quality database show that there indeed exists a linear dependency between Q_t and OCR (Figure 4.12). The best fit relationship obtained from this data is expressed by equation [14]:

[14] $$OCR = 0.20 + 0.39 \cdot Q_t \qquad r^2 = 0.43$$

Multivariable linear regression was used to improve the r^2 of equation [14], resulting in equation [15]:

[15] $$OCR = 0.85 + 0.44 \cdot Q_t - 0.05 \cdot PI \qquad r^2 = 0.63$$

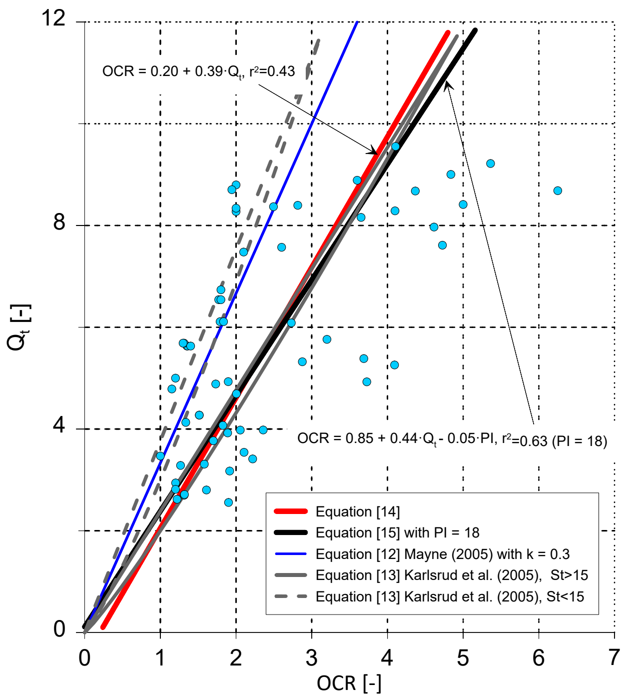

Figure 4.12 Relation between OCR and Q_t.

5 Evaluation of CPTU correlations

The correlations determined in Chapter 4 are evaluated and validated against block sample data points from four test sites in Norway located at Koa, Møllenberg (2 locations), Nybakk-Slomarka (three locations) and Skatval. For these sites, available s_u^C values from CAUC tests are used to validate the correlations.

In addition to the equations in Chapter 4, CPTU correlations proposed by Karlsrud et al. (2005) (see Eqs. [16], [17], [18], [19] below) which are currently used in onshore practice, are included in the comparison.

[16] $N_{kt} = 7.8 + 2.5logOCR + 0.082PI$ $S_t < 15$

[17] $N_{kt} = 8.5 + 2.5logOCR$ $S_t > 15$

[18] $N_{\Delta u} = 6.9 - 4.0logOCR + 0.07PI$ $S_t < 15$

[19] $N_{\Delta u} = 9.8 - 4.5logOCR$ $S_t > 15$

5.1 Koa

The clay at Koa site is a low-medium plastic clay. The plasticity index varies between 7-13, with average water content of 30%. The sensitivity varies in the range 10 to 90. A CRS tests at 8.90 m depth indicate OCR = 3.70 – 4.0 according to different methods of interpretation.

The samples collected at Koa are miniblock (Ø160 mm) samples since it was very difficult to access the area with the equipment for Sherbrook samples (Ø250 mm) (difficulties due to weather conditions at the time of sampling). The quality of the miniblock samples is similar to the quality of 72 mm samples for oedometer test data (that show quality 3). For CAUA data, the quality of miniblock samples is better (quality 1) than the 72 mm samples (quality 2).

As shown in Figure 5.1, equations [10] - [14] do not seem to capture the OCR measured from the available CRS test. This mismatch can be justified by the uncertainty in the ground water level at the site which influences the calculation of the effective in situ stresses. The best fit of equation [12] to the OCR data points is obtained for *k* = 0.50.

Figure 5.2 shows the interpreted s_u^C versus depth. CAUC tests at 5.36 m and 8.90 m depth are used to evaluate the different correlations. OCR from equation [12] is used as reference OCR to evaluate equation [6]. Equation [4] is highly dependent on OCR and therefore shows high variation in the predicted s_u^C values.

Equations [1], [2], [16] and [17] seem to slightly underestimate s_u^C by 10% or lower at 8.90 m depth. On the other hand, equation [3], [5], [18] and [19] may overestimate s_u^C in more than 10%. Equation by Karlsrud and Hernandez-Martinez (2013) and [6] slightly overestimate s_u^C by 10% or lower.

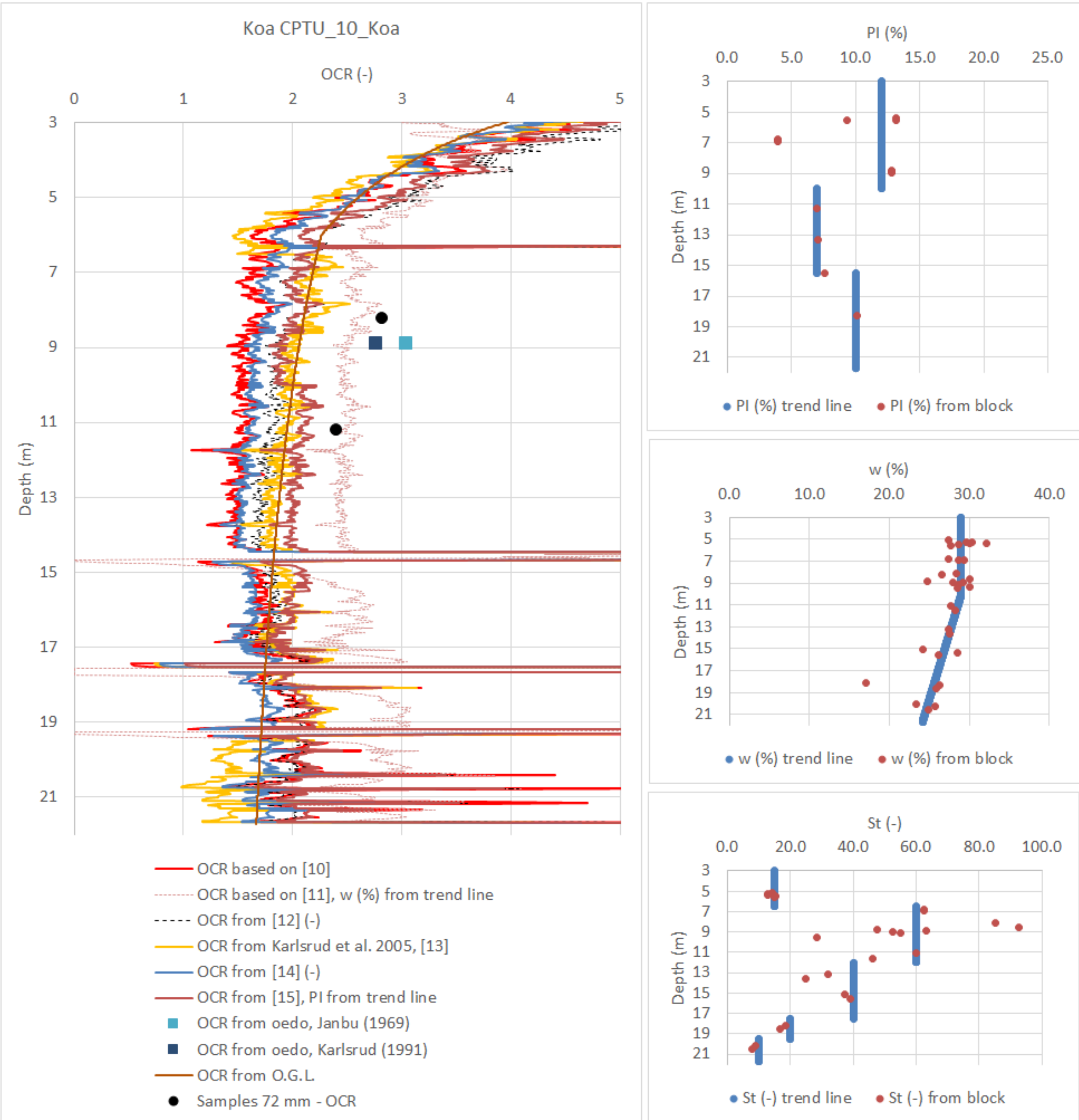

Figure 5.1 Interpreted OCR and variation of basic properties versus depth at Koa site. OGL: original ground level.

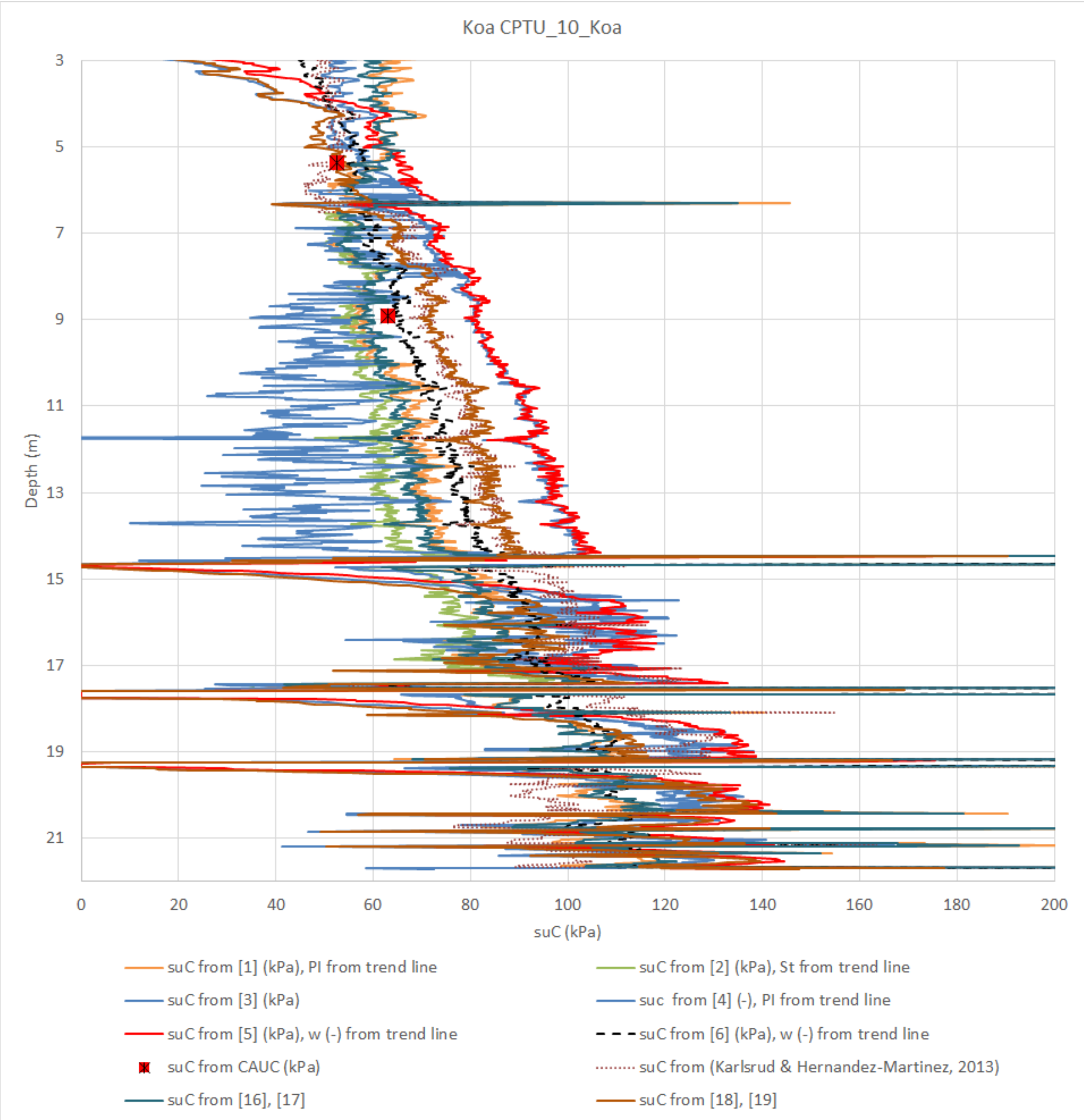

Figure 5.2 Interpreted s_u^C versus depth at Koa site.

5.2 Møllenberg 809

The clay at Møllenberg 809 site is a low to medium plastic clay. The plasticity index varies between 5 and 15, with average water content of 30%. The sensitivity is in the range 3-18. A CRS test at 19.5 m depth indicates OCR = 1.47 – 1.84 according to different methods of interpretation.

As shown in Figure 5.3, except for equation [11] that seems to overestimate OCR, the other proposed models for OCR seems to capture the OCR measured from the test. The best fit of equation [12] to the OCR data points is obtained for $k = 0.38$.

Figure 5.4 shows the interpreted s_u^C versus depth. CAUC tests at 12.9 m and 19.5 m depth are used to evaluate the different correlations. It must be highlighted that there is a mismatch of about 15 kPa between the *in situ* stress and the vertical consolidation stress in the test 12.90 m. Block sample database gives approx. 15 kPa lower *in situ* stress compared to CPTU interpretation sheet. Therefore, s_u^C at 12.90 is expected to be higher than what measured. Based on that, higher weight is given to the CAUC test at 19.5 m. Furthermore, OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations [1], [3], [4], [6], [16], [17], [18], [19] and by Karlsrud and Hernandez-Martinez (2013) are able to predict quite accurately s_u^C from the CAUC test at 19.5 m depth. On the other hand, s_u^C at 12.9 m depth is under- and overestimate with the majority of the equations. A better agreement between the different models can be observed above 12 m. Equation [2] was not evaluated since St < 30.

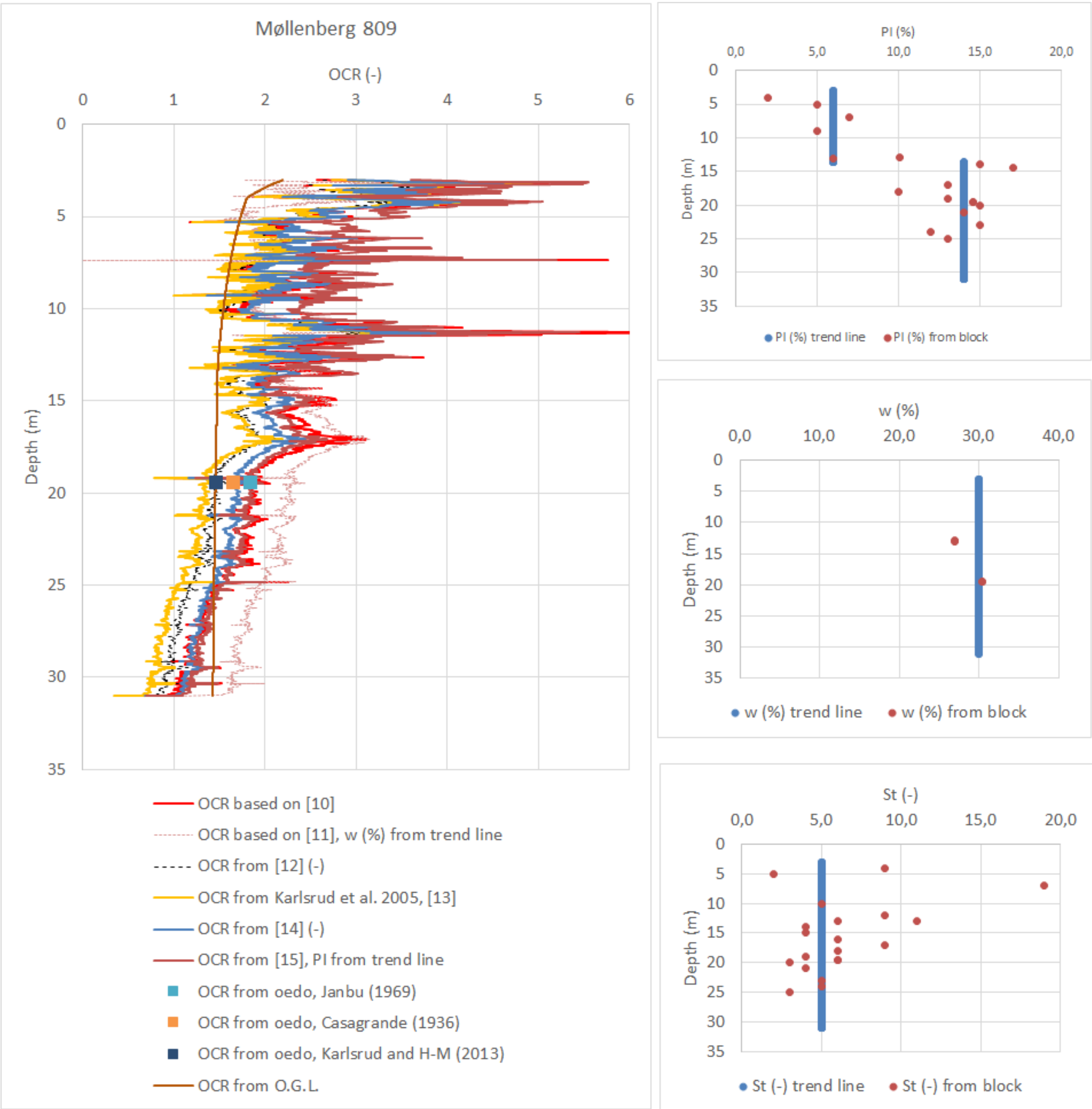

Figure 5.3 Interpreted OCR and variation of basic properties versus depth at Møllenberg 809 site. OGL: original ground level.

Figure 5.4 Interpreted s_u^C versus depth at Møllenberg 809 site.

5.3 Møllenberg 823

The clay at Møllenberg 823 site is a low plastic clay. The plasticity index varies between 5 and 8, with average water content of 38%. The sensitivity is about 200. CRS tests at 9.2 m and 18.2 m depth indicate OCR = 1.50 – 2.0 and 1.40 – 1.78, respectively, according to different methods of interpretation.

As shown in Figure 5.5, equations [10], [12], [14] seem to capture the OCR measured from the tests. The best fit of equation [12] to the OCR data points is obtained for k = 0.45.

Figure 5.6 shows the interpreted s_u^C versus depth. CAUC tests at 9.2 m and 18.2 m depth are used to evaluate the different correlations. It must be highlighted that there is a mismatch of about 30 kPa between the *in situ* stress and the vertical consolidation stress in the test at 18.2 m. Block sample database gives approx. 30 kPa lower *in situ* stress compared to CPTU interpretation sheet. Therefore, s_u^C at 18.2 m is expected to be higher than what measured. Based on that, higher weight is given to the CAUC test at 9.2 m. Furthermore, OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations [1], [2], [6], by Karlsrud and Hernandez-Martinez (2013), [16], [17], [18] and [19] are able to predict quite accurately s_u^C from the CAUC test at 9.2 m depth. If the CAUC test at 18.2 m had been consolidated to the correct in situ stresses, equations [1], [2], [5] and [6] would have been able to predict quite well s_u^C. Equation [4] underestimate s_u^C for both depths, since it is highly dependent on OCR.

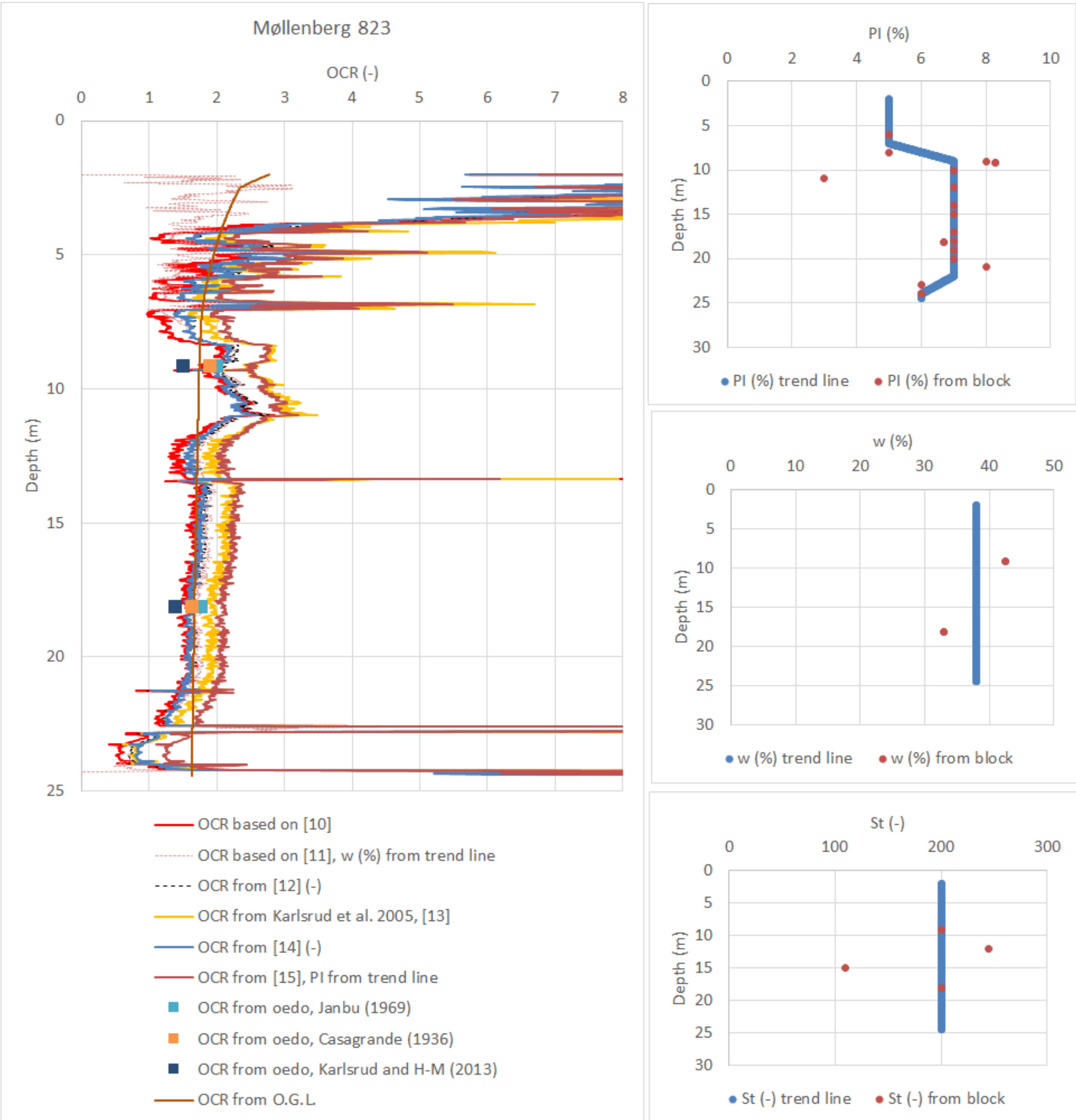

Figure 5.5 Interpreted OCR and variation of basic properties versus depth at Møllenberg 823 site. OGL: original ground level.

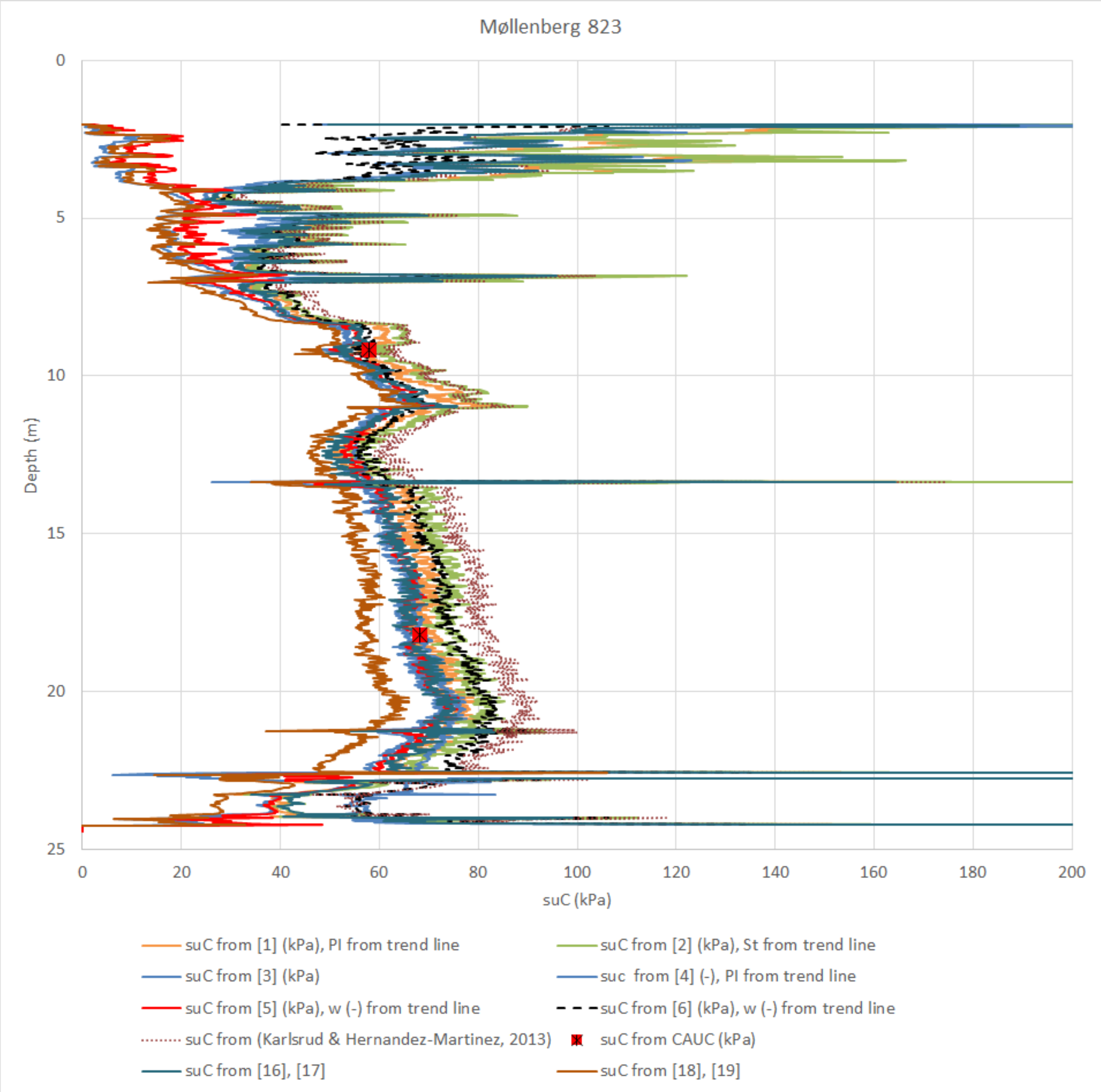

Figure 5.6 Interpreted s_u^C versus depth at Møllenberg 823 site.

5.4 Nybakk-Slomarka C2371

The clay at Nybakk-Slomarka C2371 site is a low-medium plastic clay. The plasticity index varies between 7 and 20, with water content of 25-40%. The sensitivity reaches values greater than 200. CRS tests at different depths indicate OCR = 2.2 – 5.2, decreasing with increasing depth, according to different methods of interpretation.

As shown in Figure 5.7, equations [10], [13], [14], [15] seem to underestimate the OCR interpreted from CRS test. Below 10 m depth, eq. [11] captures fairly well the CRS test results. The best OCR fit is obtained using equation [12] with $k = 0.55$.

Figure 5.8 shows the interpreted s_u^C versus depth. CAUC tests at three different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Overall, equations [6] and those by Karlsrud and Hernandez-Martinez (2013) give the best fit to the data points. Equation [1] seem able to capture the s_u^C down to 11 m depth. Below 11 m, equations [18] and [19] also capture s_u^C from CAUC. Equation [4] underestimate s_u^C before 14 m depth and after that it shows strong variations due to the highly dependency on OCR that it shows. The clay at this site is sensitive with St > 15 from ca. 14 m. This can explain the observed jump in the estimation of undrained shear strength from 11 m to 15 m with some of the correlations.

L'heureux et al. (2018) presents results of empirical correlations between CPTU parameters, the undrained shear strength and the overconsolidation ratios for this clay (Rakkestad clay) based on regression analyses on a local database. A better match with the relationships based on the block sample correlations was obtained in that study. Karlsrud et al. (2005) relationships seemed to underestimate the OCR of Rakkestad clay. The differences were significant throughout the profile. Differences were also observed in the case of the interpreted undrained shear strength where developed equations seem to capture the laboratory values at depths over 11 m. Below this depth, they underestimate the value for undrained shear strength obtained from a block sample.

Comparing the correlations presented in this report with the ones proposed by L'heureux et al. (2018) can be concluded that:

- OCR correlations from L'heureux et al. (2018) estimate better the laboratory values, and
- s_u^C correlations from this report (Equation [6]) seem to better capture the laboratory values.

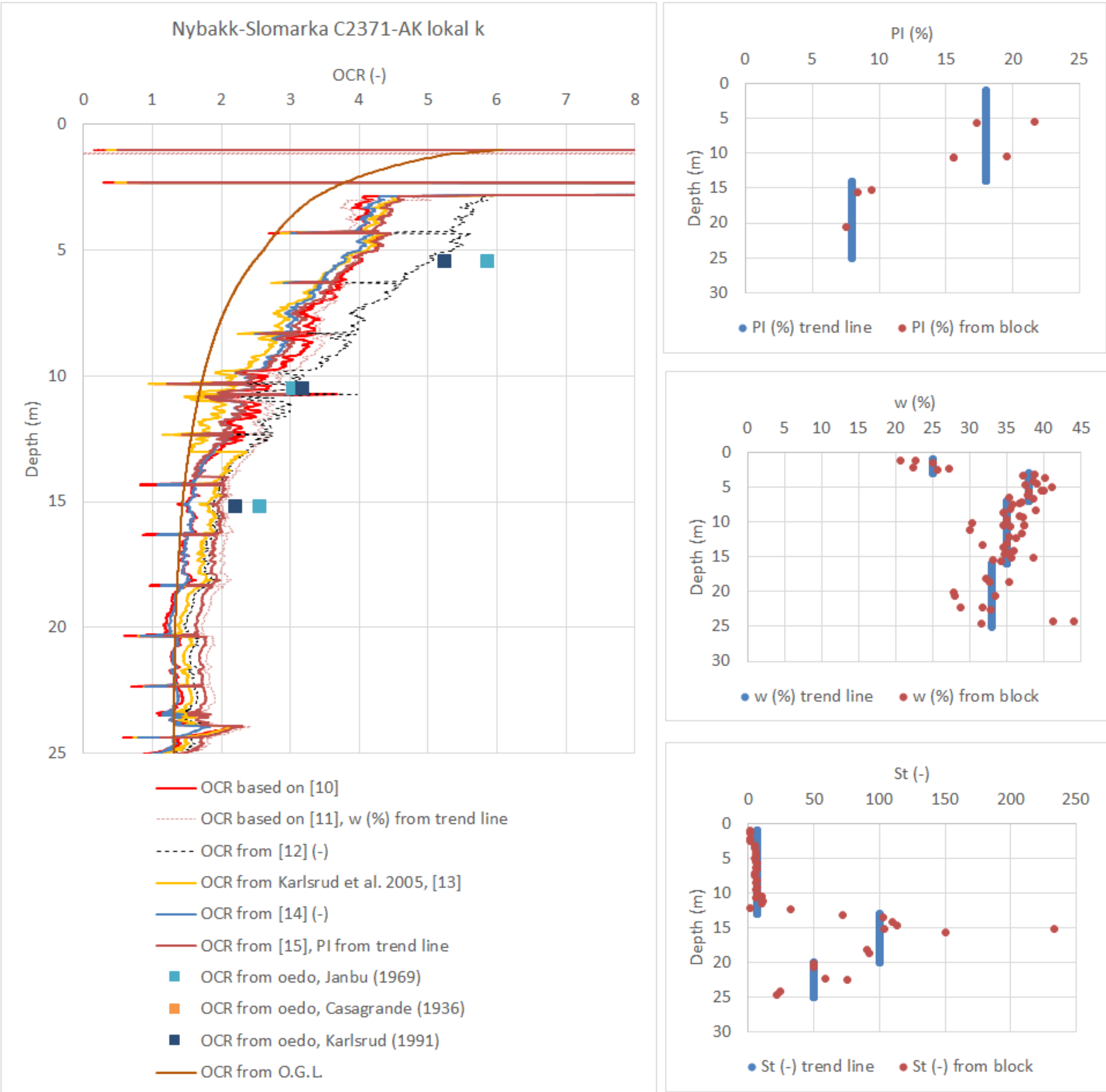

Figure 5.7 Interpreted OCR and variation of basic properties versus depth at Nybakk-Slomarka C2371 site. OGL: original ground level.

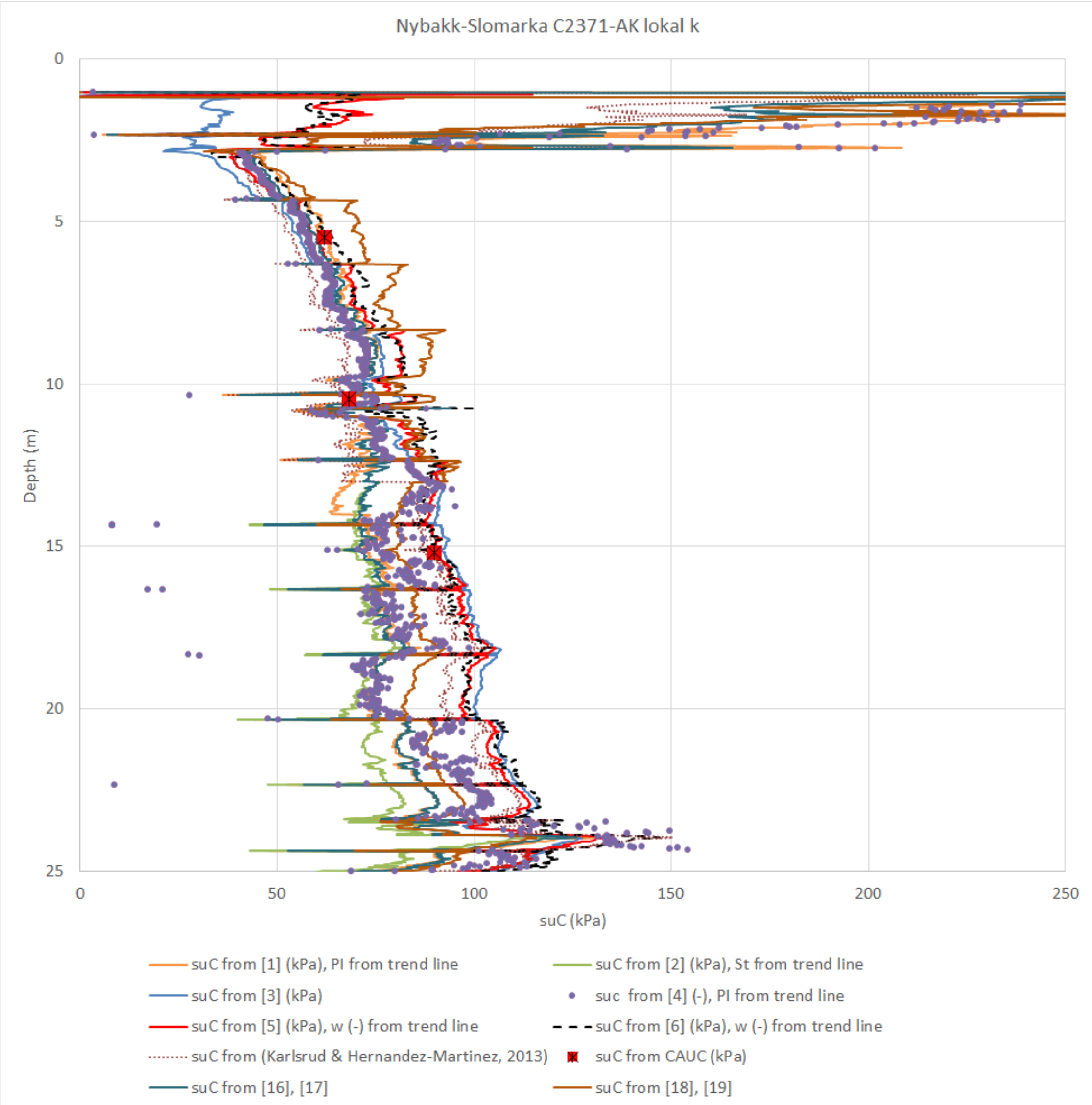

Figure 5.8 Interpreted s_u^C versus depth at Nybakk-Slomarka C2371 site.

5.5 Nybakk-Slomarka C2411

The clay at Nybakk-Slomarka C2411 site is a low-medium plastic clay. The plasticity index varies between 11 and 18, with average water content of 35%. The sensitivity ranges between 15 and 20. CRS tests at different depths indicate OCR = 2.9 – 5.3, decreasing with increasing depth, according to different methods of interpretation.

As shown in Figure 5.9, equations [10], [14], [15] seem to underestimate the OCR interpreted from CRS test. Equations [11], [12], [13] capture fairly well the CRS test results. The best fit of equation [12] to the OCR data points is obtained for $k = 0.55$.

Figure 5.10 shows the interpreted s_u^C versus depth. CAUC tests at three different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation and [6]. Overall, equations by Karlsrud and Hernandez-Martinez (2013), [6], [16], [17] give the best fit to the data points. The other equations overestimate s_u^C.

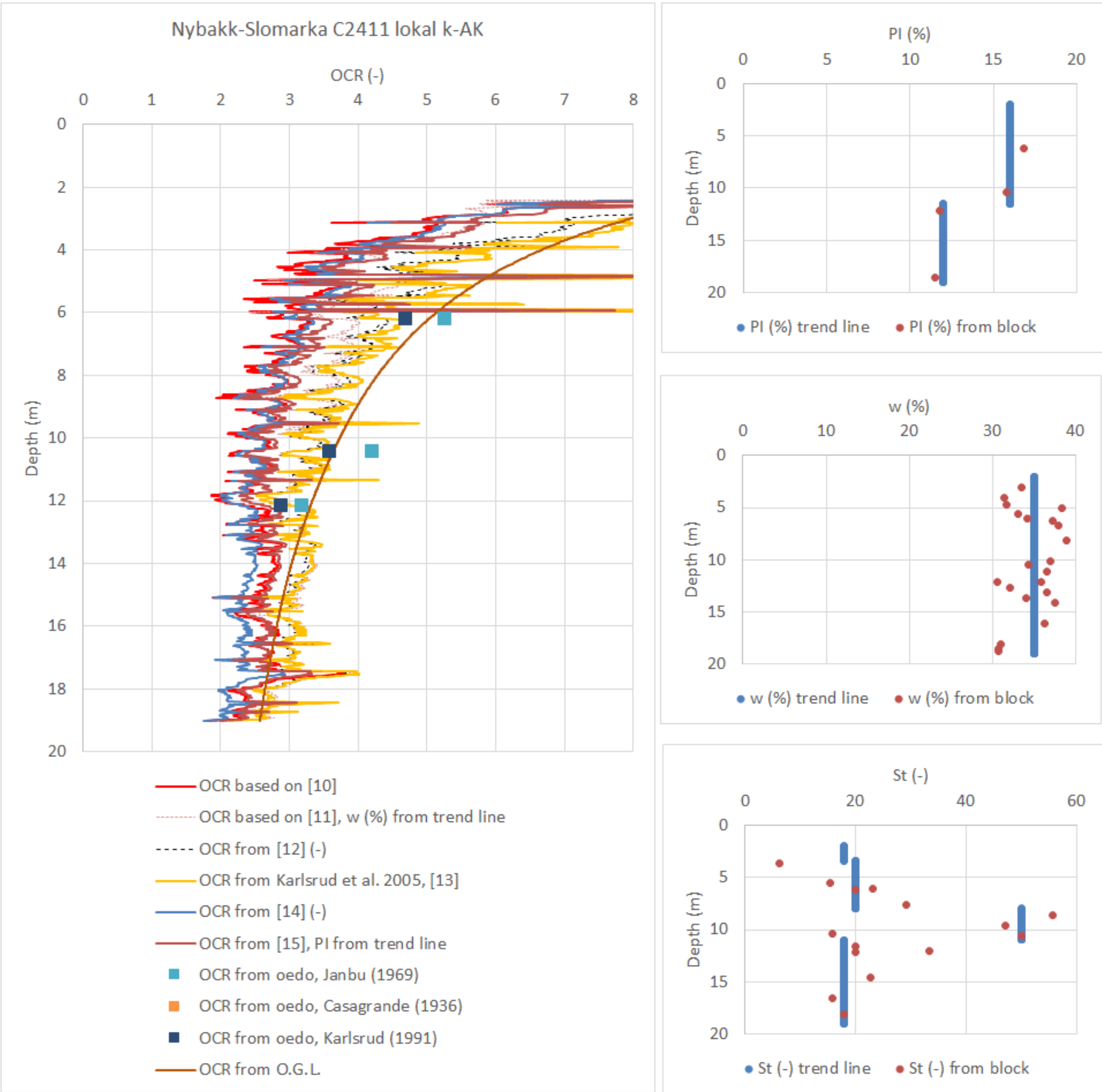

Figure 5.9 Interpreted OCR and variation of basic properties versus depth at Nybakk-Slomarka C2411 site.

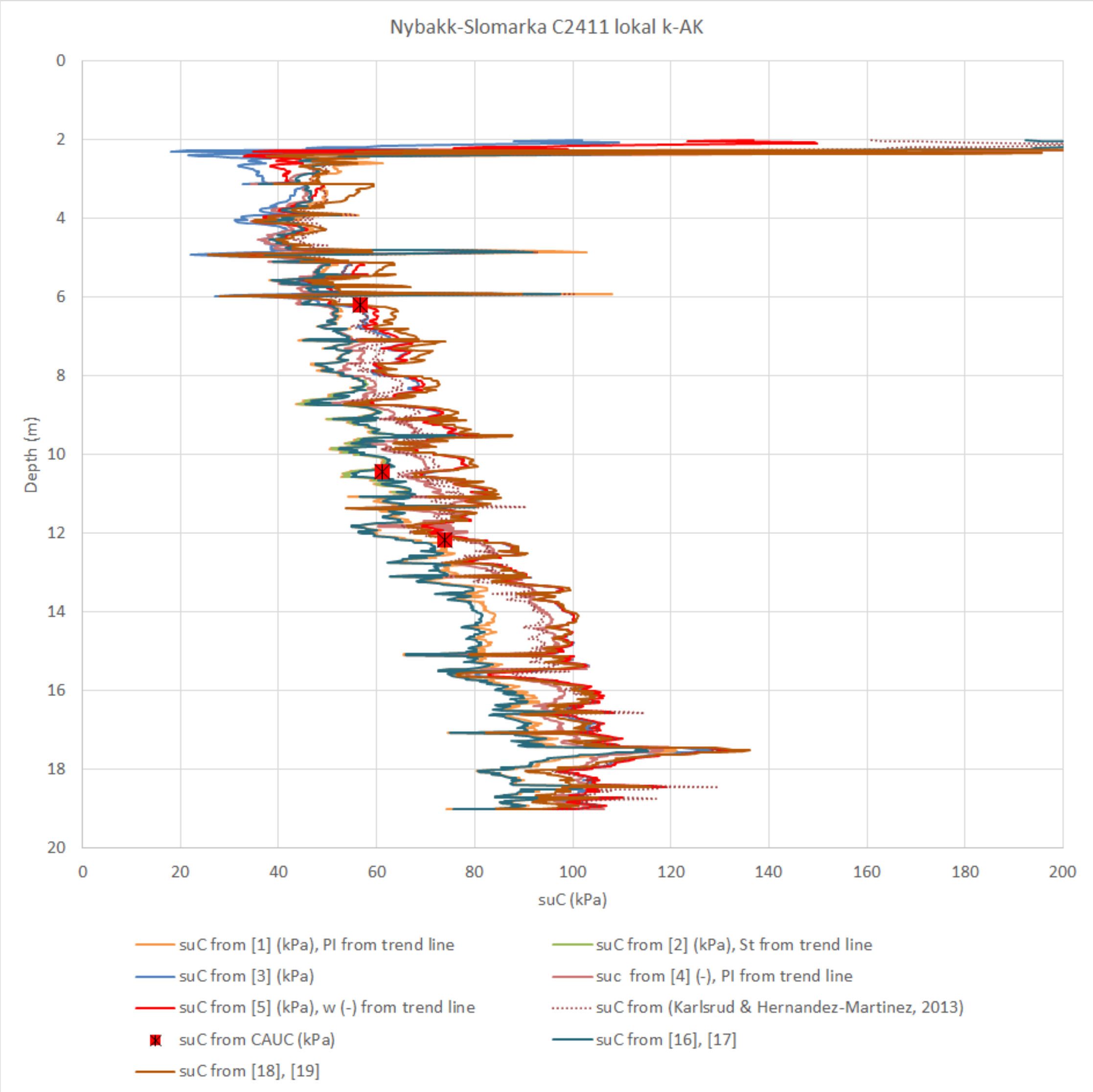

Figure 5.10 Interpreted s_u^C versus depth at Nybakk-Slomarka C2411 site.

5.6 Nybakk-Slomarka C2284

The clay at Nybakk-Slomarka C2284 site is a medium plastic clay. The plasticity index varies between 15 and 24, with water content of 40-50%. The sensitivity ranges between 8 and 20. CRS tests at different depths indicate OCR = 1.22 – 2.1, decreasing with increasing depth, according to different methods of interpretation.

As shown in Figure 5.11, equations [10], [13], [15] seem to underestimate the OCR interpreted from CRS test. Equations [11], [12], [14] capture fairly well the CRS test results. The best fit of equation [12] to the OCR data points obtained from Karlsrud and Hernandez-Martinez's (2013) method is obtained for $k = 0.47$.

Figure 5.12 shows the interpreted s_u^C versus depth. CAUC tests at three different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Overall, equations [4] and [6] give the best fit to the data points. Some other equations over- and underestimate s_u^C by ±10%.

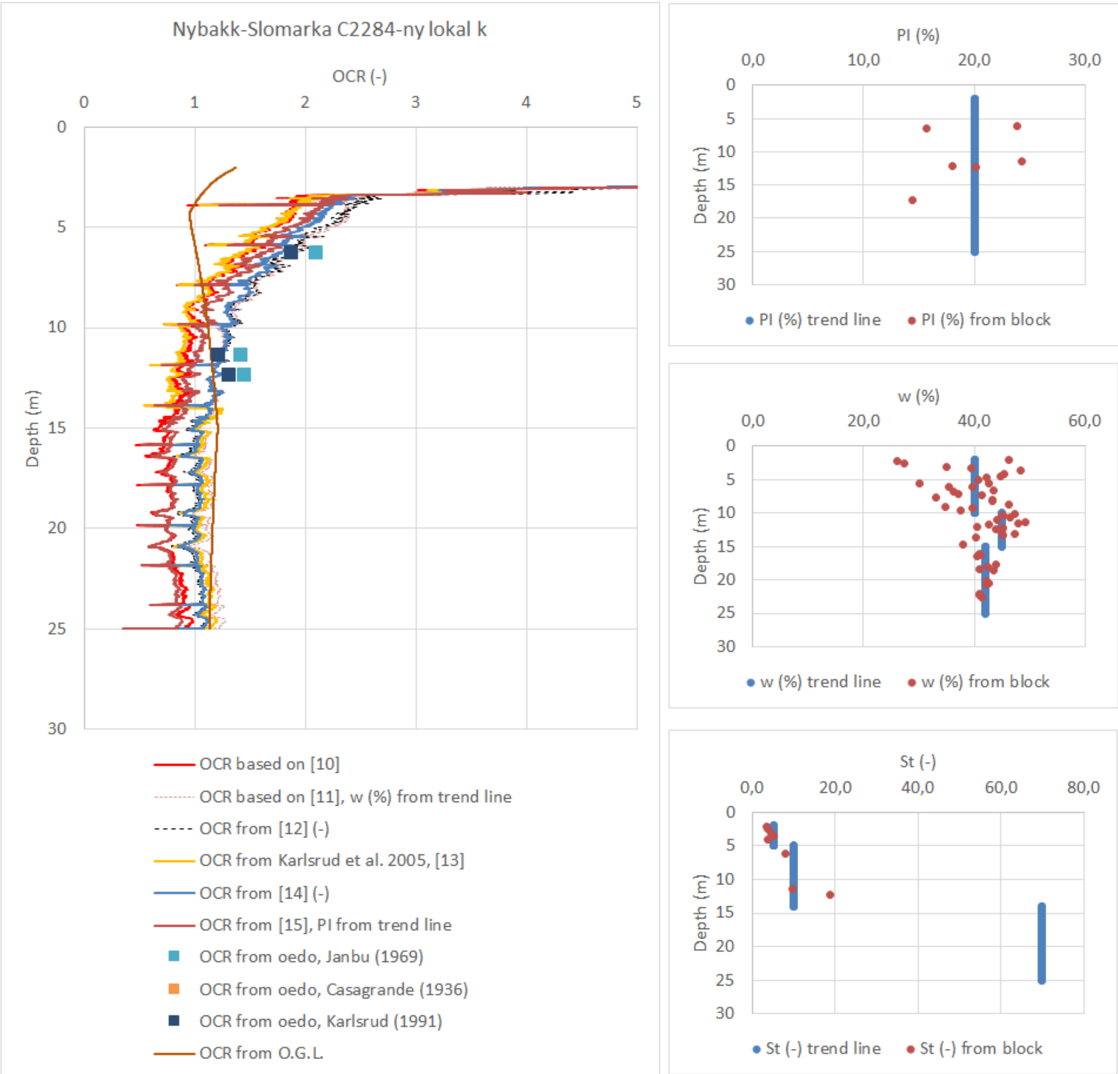

Figure 5.11 Interpreted OCR and variation of basic properties versus depth at Nybakk-Slomarka C2284 site.

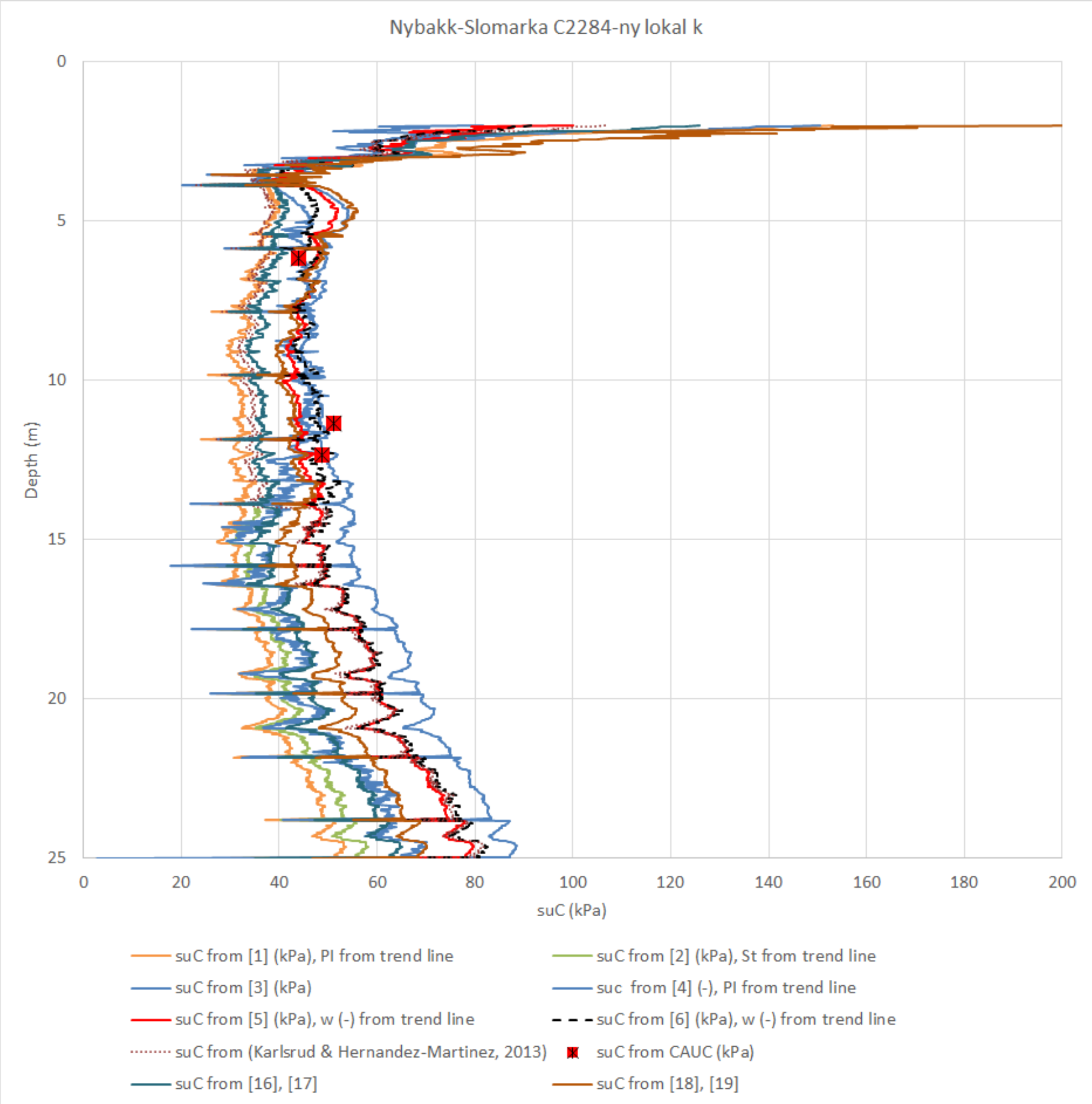

Figure 5.12 Interpreted s_u^C versus depth at Nybakk-Slomarka C2284 site.

5.7 Skatval

The clay at Skatval site is a low to medium plastic clay. The plasticity index varies between 7.5 and 17, with average water content of 34%. The sensitivity varies between 4 and 70. CRS tests between 5 and 8 m depth indicate OCR = 1.86 – 3.10, according to interpretation method by Janbu (1969). Other interpretation methods for p'_c were not tested for this site.

As shown in Figure 5.13, equation [10] seems to slightly underestimate the OCR, while the other equations are able to better predict the test results. In particular, the OCR from Janbu's method is captured by equation [12] for k = 0.45.

Figure 5.14 shows the interpreted s_u^C versus depth. CAUC tests at four different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations by Karlsrud and Hernandez-Martinez (2013), [2], [6] [16], [17], [18], [19] seem able to predict quite accurately s_u^C from the CAUC tests below 5 m depth. The equations spread over a range of 30-35 kPa below 12 m depth. The CAUC test at 4.55 m depth could not be captured by any of the tested correlations.

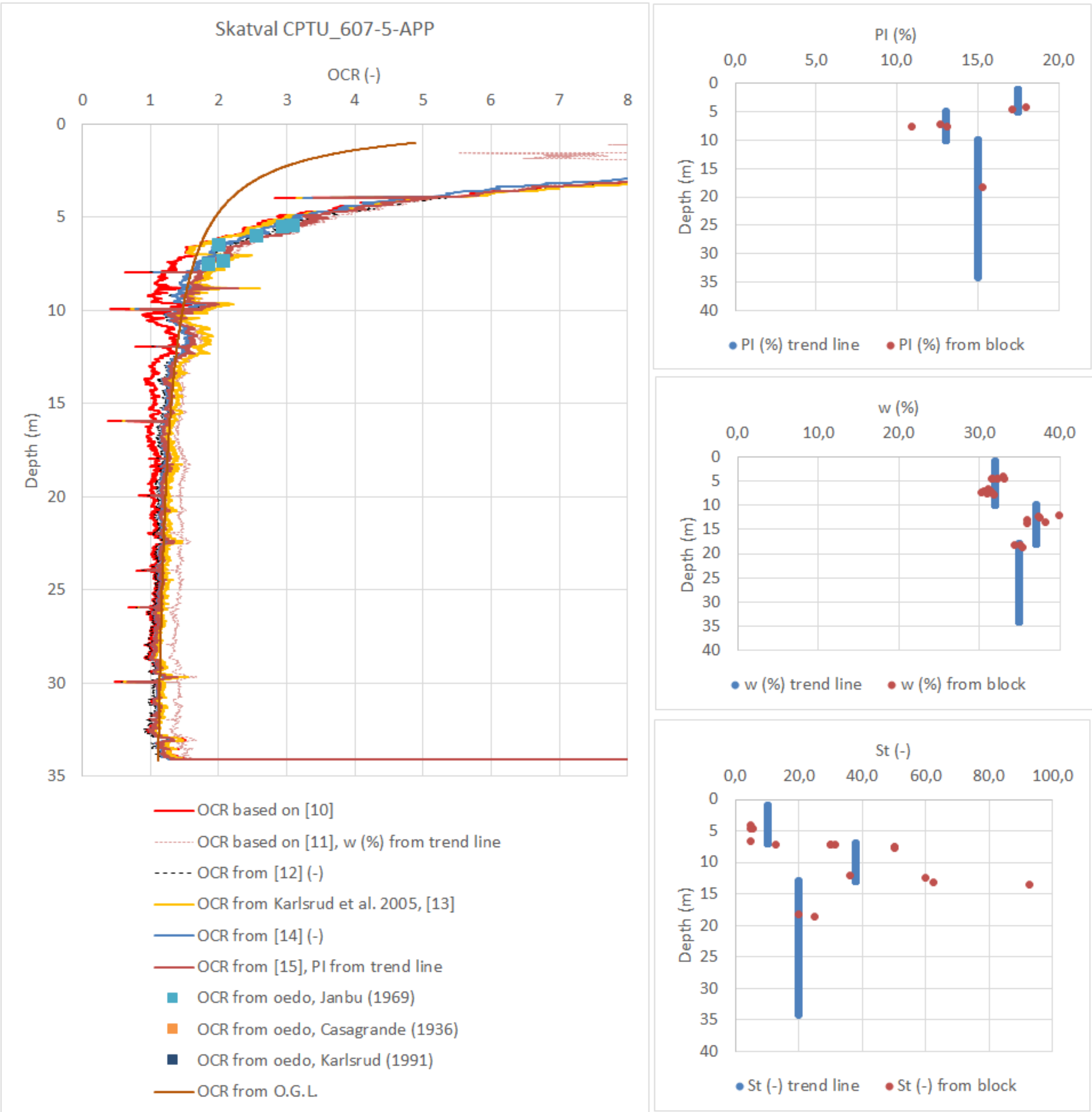

Figure 5.13 Interpreted OCR and variation of basic properties versus depth at Skatval site.

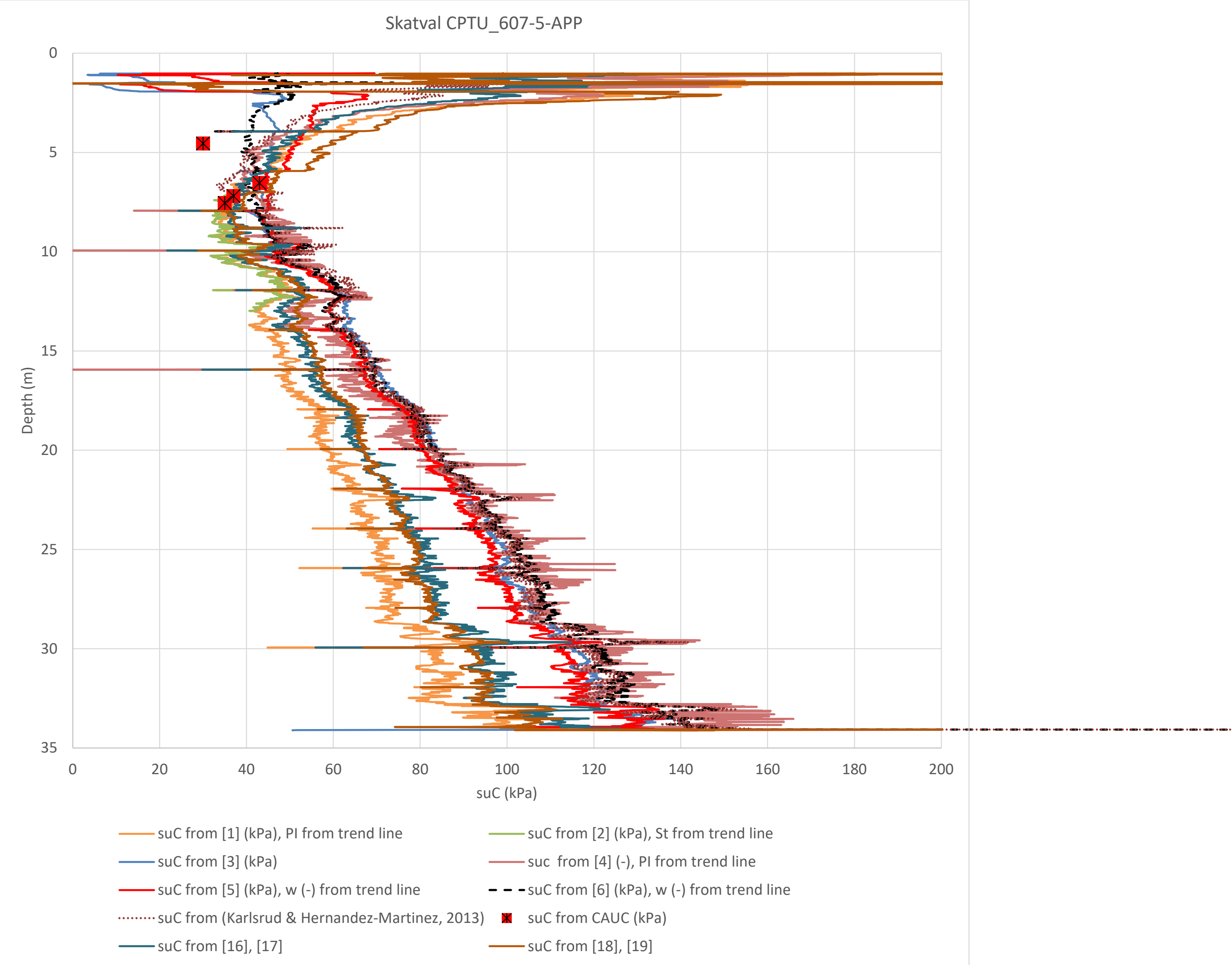

Figure 5.14 Interpreted s_u^C versus depth at Skatval site.

5.8 Tiller-Flotten TILC01

The clay at Tiller-Flotten site is a low to highly plastic clay. The plasticity index varies between 6 and 35, with average water content of 45%. The sensitivity varies between 10 and 250. CRS tests between 8 and 17 m depth indicate OCR = 1.8 – 2.9, according to interpretation method by Janbu (1969).

The Tiller-Flotten site has non-hydrostatic conditions. The sensitive clay layer, at Flotten goes from about 7-20 m depth. There is still clay under with some coarse material layers (20-33 m depth) and clay under this layer. The upper layer (0-7 m) is not-sensitive clay with a dry crust in the first meters.

As shown in Figure 5.15 equation [10], [11], [14] and [15] are able to better predict the test results before 13 m depth. After that, the equations overestimate the OCR with the exception of equation [14]. Equation [13] overestimate the OCR values from 7 m and deeper. The OCR from CRS tests is captured by equation [12] for $k = 0.44$.

Figure 5.14Figure 5.16 shows the interpreted s_u^C versus depth. CAUC tests at seven different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations [4], [16] and [17] seem able to predict quite accurately s_u^C from the CAUC tests. The other equations seem to overestimate the test values after 7 m where the sensitive layer starts.

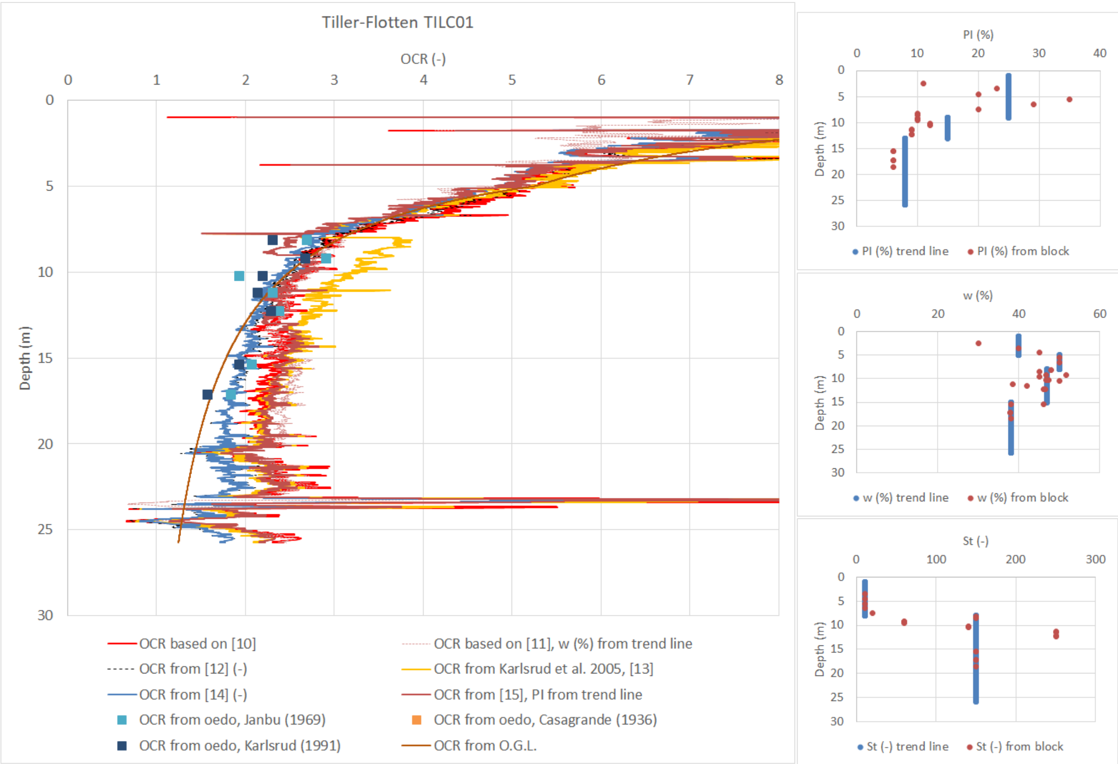

Figure 5.15 Interpreted OCR and variation of basic properties versus depth at Tiller-Flotten TILC01 site.

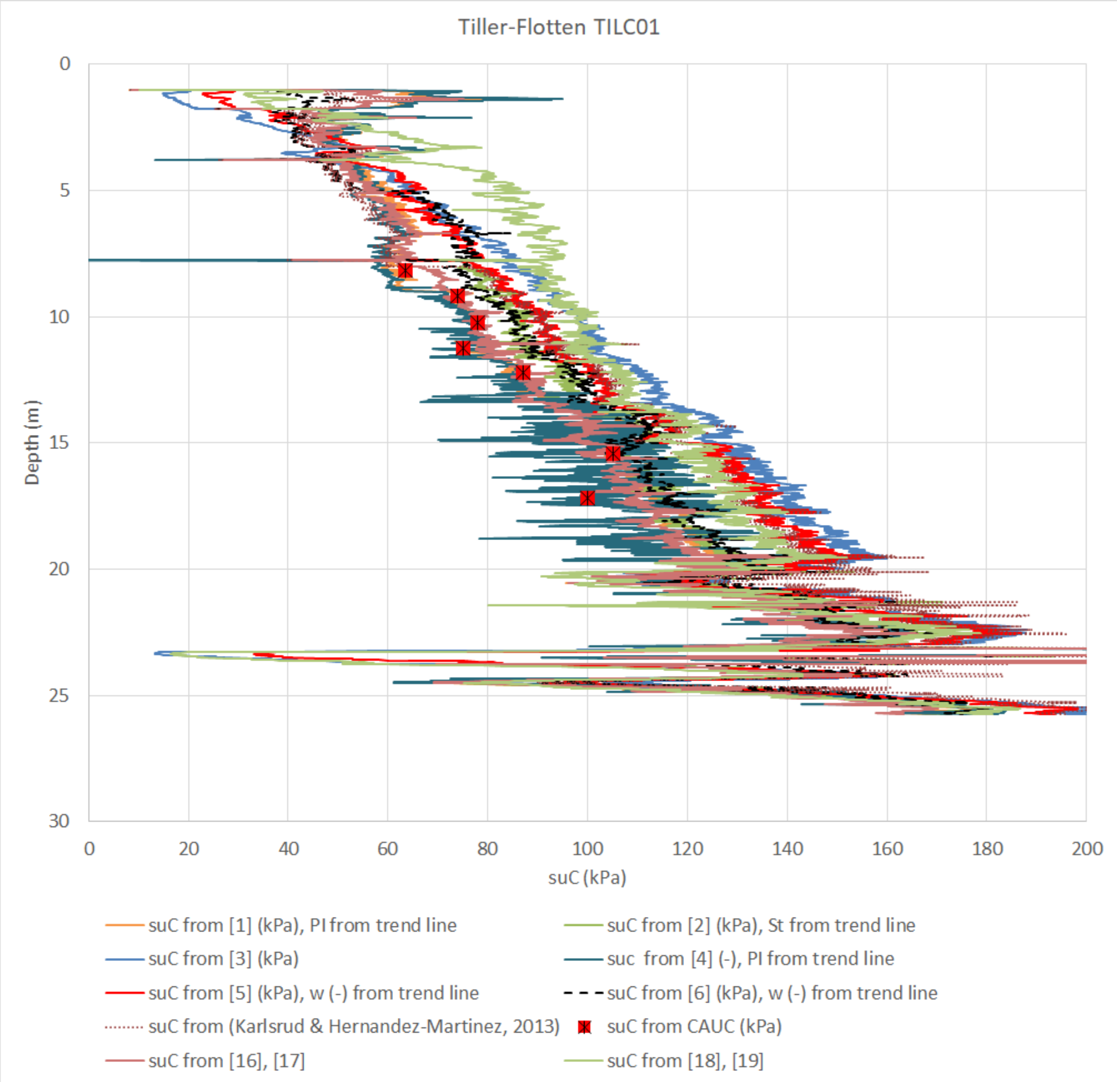

Figure 5.16 Interpreted s_u^C versus depth at Tiller-Flotten TILC01 site.

5.9 Tiller-Flotten TILC18

The clay at Tiller-Flotten site is a low to highly plastic clay. The plasticity index varies between 6 and 35, with average water content of 45%. The sensitivity varies between 10 and 250. CRS tests between 8 and 17 m depth indicate OCR = 1.8 – 2.9, according to interpretation method by Janbu (1969).

The Tiller-Flotten site has non-hydrostatic conditions. The sensitive clay layer, at Flotten goes from about 7-20 m depth. There is still clay under with some coarse material layers (20-33 m depth) and clay under this layer. The upper layer (0-7 m) is not-sensitive clay with a dry crust in the first meters.

As shown in Figure 5.17 equation [14] is able to better predict the test results, while the other equations overestimate the OCR. The OCR from CRS tests is captured by equation [12] for $k = 0.44$.

Figure 5.14Figure 5.18 shows the interpreted s_u^C versus depth. CAUC tests at seven different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations [1], [4], [16] and [17] seem able to predict quite accurately s_u^C from the CAUC tests. The other equations seem to overestimate the test values.

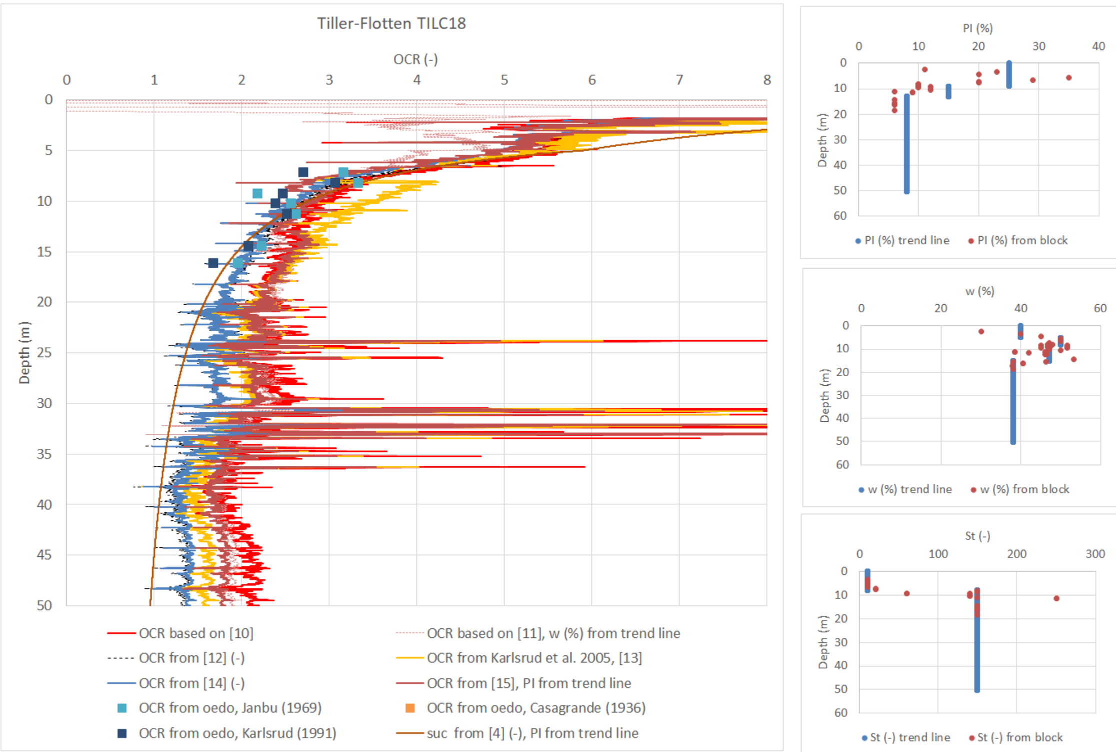

Figure 5.17 Interpreted OCR and variation of basic properties versus depth at Tiller-Flotten TILC18 site.

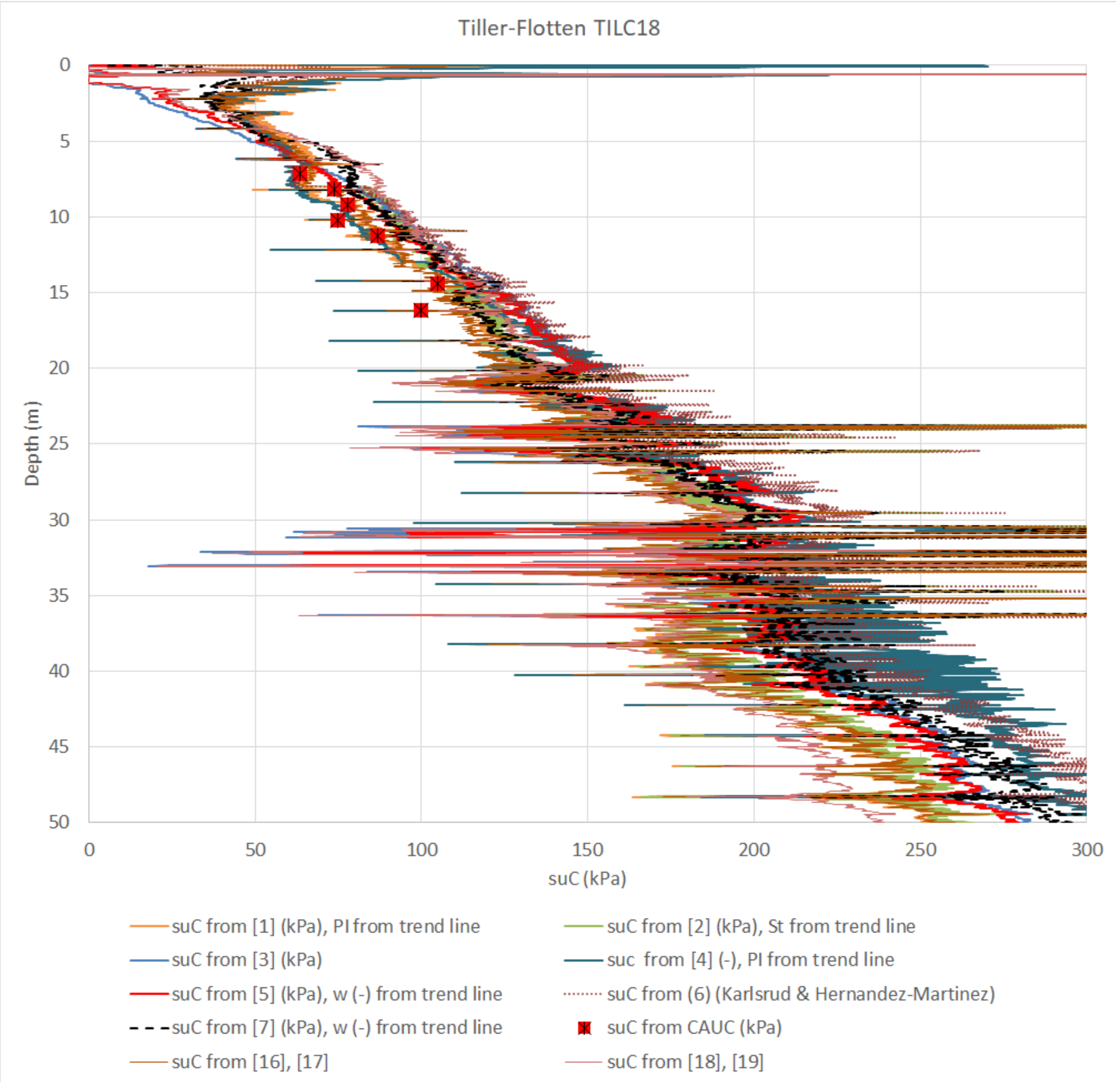

Figure 5.18 Interpreted s_u^C versus depth at Tiller-Flotten TILC18 site.

5.10 Onsøy ONSC01

The clay at Onsøy site is a medium to highly plastic clay. The plasticity index varies between 19 and 45, with average water content of 58%. The sensitivity varies between 10 and 47. CRS tests between 7 and 15 m depth indicate OCR = 1.2 – 1.9, according to interpretation method by Janbu (1969).

As shown in Figure 5.19, the correlations are spread and equation [10] and [11] are able to better predict the test results, while the other equations over- and underestimate OCR. Equations [13], [14] and [15] do not seem to capture the test values. The OCR from CRS tests is captured by equation [12] for $k = 0.38$.

Figure 5.20 shows the interpreted s_u^C versus depth. CAUC tests at six different depths are used to evaluate the different correlations. The OCR from equation [12] is used as reference OCR to evaluate equation [6].

Equations [5] seem able to predict quite accurately s_u^C from the CAUC tests before 14 m depth. After that, equation [6] tends to approach to the test values. The other equations seem to underestimate the test values.

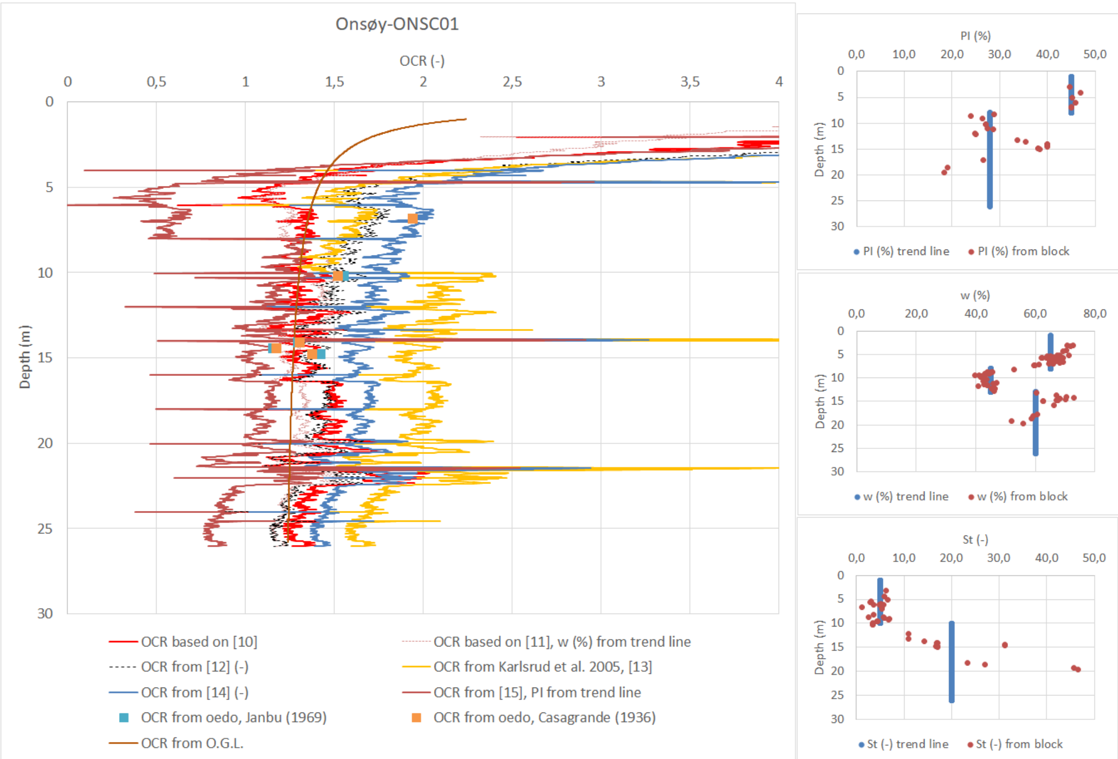

Figure 5.19 Interpreted OCR and variation of basic properties versus depth at Onsøy ONSC01 site.

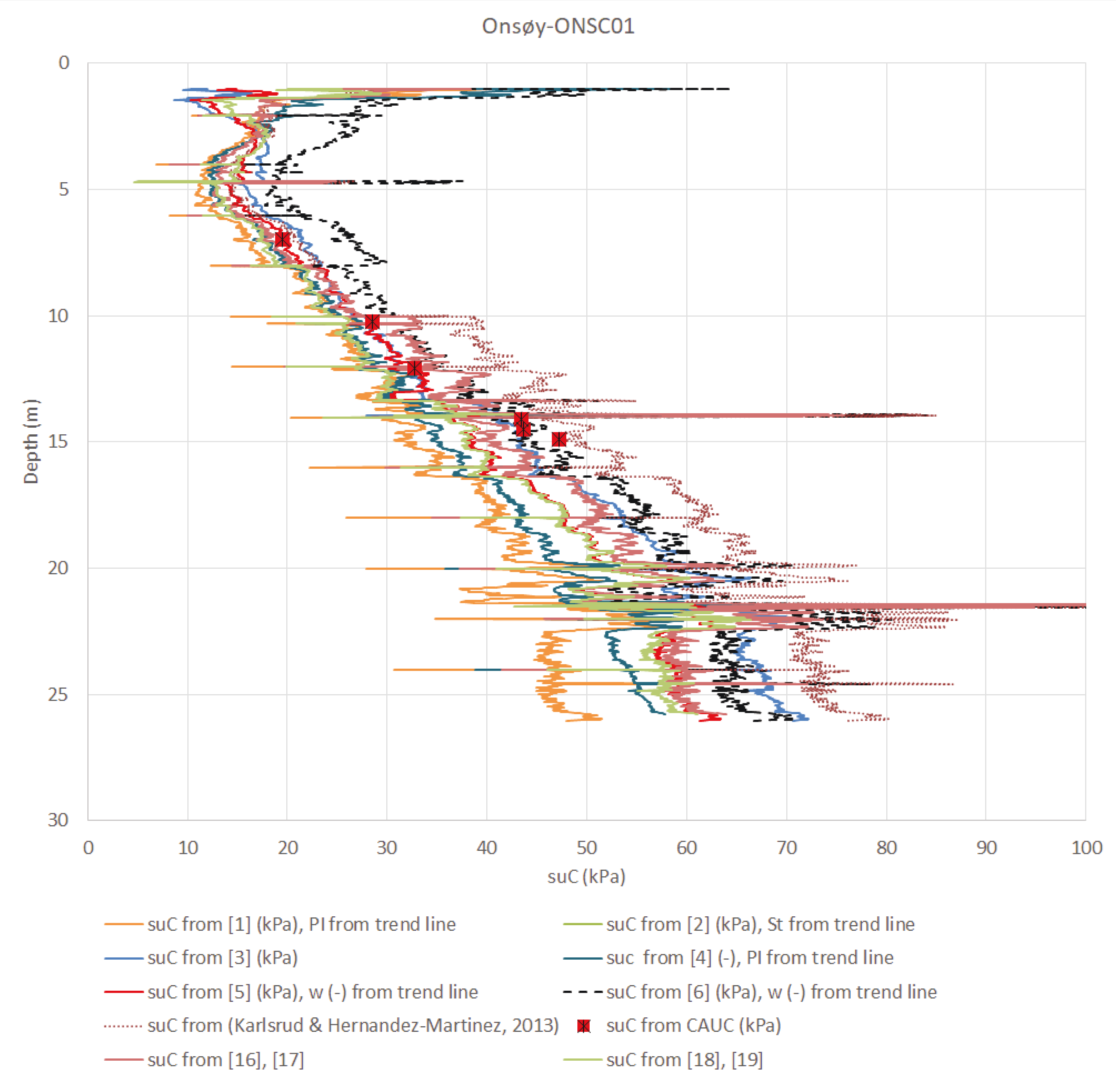

Figure 5.20 Interpreted s_u^C versus depth at Onsøy ONSC01 site.

5.11 Discussion

Sections 5.1 to 5.10 have presented the application of the correlations established in Section 4 to ten different clay sites in Norway. Figure 5.21 and Figure 5.22 show a summary of the accuracy in the prediction of OCR and s_u^C with the different equations. Based on this study, it seems that:

1) For OCR:
   - Equations [12] and [14] for OCR can fairly well capture the OCR of the tested sites with differences of maximum ±10%. This was observed in 60% and 46% of the cases, respectively.

- Equation [11] for p_c' can also fairly well capture the OCR of the tested sites with differences of maximum ±10%, based on the available test results. This was observed in 43% of the cases.
- The fitting of equation [12] shows a variation of k between 0.44 – 0.47. The sites were a higher or lower k value had to be used were considered as "difficult to fit" to the OCR from laboratory tests.

2) For s_u^C:
- The best fit to the test results were found to be equations [4], [6], [16], [17]. The difference respect to the laboratory values are up to ±10% in more than 55% of the cases evaluated.
- While Eq. [1], which defines N_{kt} as a function of PI, seemed to work relatively well, Eq. [6] and by Karlsrud and Hernandez-Martinez's (2013), which define s_u^C as a function of OCR, seemed, in general, more robust. However, the equation by Karlsrud and Hernandez-Martinez's (2013) over predicted the laboratory values with more than 20% in 32% of the cases evaluated.
- The accuracy of the equations sowing "the best fit" are, nevertheless, dependent upon the reliability of the modelled OCR, water content and plasticity index profile.

	Lower in			Higher in	
	more than 20%	10%-20%	±10%	10%-20%	more than 20%
OCR based on [10]	34 %	9 %	23 %	11 %	23 %
OCR based on [11], w (%) from block	9 %	14 %	40 %	14 %	23 %
OCR based on [11], w (%) from trend line	6 %	9 %	43 %	20 %	23 %
OCR from [12] (-)	3 %	9 %	60 %	20 %	9 %
OCR from Karlsrud et al. 2005, [13]	17 %	11 %	11 %	6 %	54 %
OCR from [14] (-)	20 %	3 %	46 %	17 %	14 %
OCR from [15], PI from block	31 %	6 %	14 %	11 %	37 %
OCR from [15], PI from trend line	26 %	17 %	23 %	9 %	26 %
OCR from O.G.L.	20 %	17 %	46 %	11 %	6 %

Figure 5.21 Summary of accuracy in the prediction of OCR with the different equations.

	Lower in			Higher in	
	more than 20%	10%-20%	±10%	10%-20%	more than 20%
suC from [1] (kPa), PI from block	21 %	11 %	45 %	21 %	3 %
suC from [1] (kPa), PI from trend line	18 %	13 %	53 %	13 %	3 %
suC from [2] (kPa), St from block	0 %	10 %	35 %	35 %	20 %
suC from [2] (kPa), St from trend line	5 %	5 %	30 %	50 %	10 %
suC from [3] (kPa)	3 %	3 %	37 %	29 %	29 %
suc from [4] (-), PI from trend line	5 %	24 %	58 %	5 %	8 %
suc from [4] (-), PI from block	8 %	18 %	50 %	13 %	11 %
suC from [5] (kPa), w (-) from block	3 %	11 %	39 %	24 %	24 %
suC from [5] (kPa), w (-) from trend line	0 %	13 %	42 %	18 %	26 %
suC from [6] (kPa), w (-) from block	0 %	0 %	58 %	26 %	16 %
suC from [6] (kPa), w (-) from trend line	0 %	3 %	55 %	26 %	16 %
suC from (Karlsrud & Hernandez-Martinez, 2013)	5 %	8 %	32 %	24 %	32 %
suC from [16], [17]	8 %	13 %	66 %	11 %	3 %
suC from [18], [19]	5 %	21 %	21 %	26 %	26 %

Figure 5.22 Summary of accuracy in the prediction of s_u^C with the different equations.

5.11.1 Comparison between SHANSEP based equations: equation [6] and Eq. by Karlsrud and Hernandez-Martinez's (2013)

While the r^2 of Eq. by Karlsrud and Hernandez-Martinez's (2013) is unknown, Eq. [6] showed a relatively high r^2 of 0.80. A comparison between the two equations is made in Figure 5.23, Figure 5.24 and Figure 5.25. For OCR = 1, equation by Karlsrud and Hernandez-Martinez's (2013) suggests that the normalized strength (S) increases with increasing water content, while S is constant and equal to 0.32 according to eq. [6] (Figure 5.23). Larsson et al. (2007) suggested S = 0.33 (constant) for triaxial compression strength of Swedish clays.

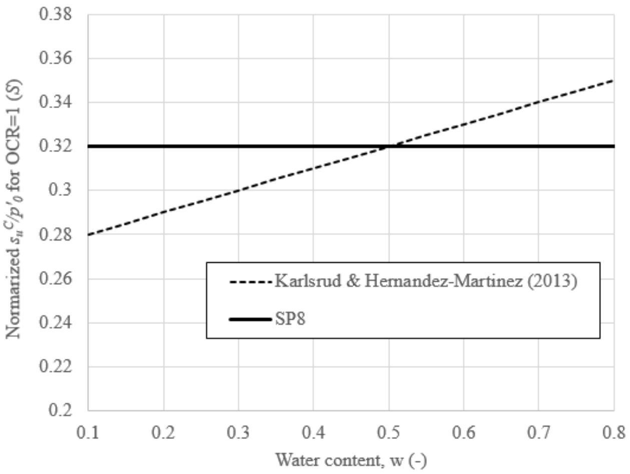

Figure 5.23 Normalized $s_u{}^C$ vs water content for OCR = 1.

According to Figure 5.24, the exponent m varies between 0.6 and 0.85 from eq. by Karlsrud and Hernandez-Martinez's (2013), while m = 0.35 – 1.15 from eq. [6], for w = 10% – 80%. Larsson et al. (2007) suggested m = 0.8 for Swedish clays. D'Ignazio et al. (2016) reported $m \approx 0.76$ for Finnish clays.

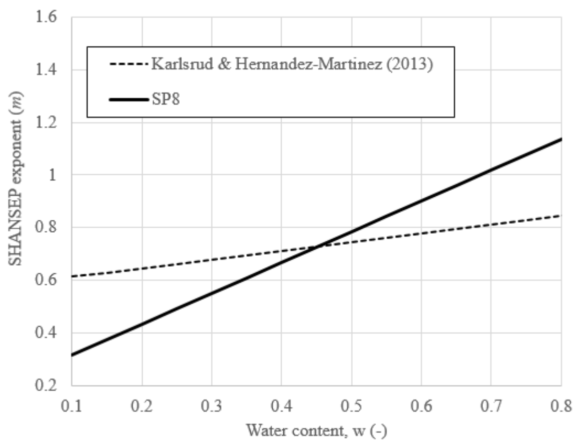

Figure 5.24 SHANSEP exponent vs water content.

Figure 5.25 illustrates the different normalized s_u^C/p'_0 predicted by eqs.by Karlsrud and Hernandez-Martinez's (2013) and [6]. For water content of 30 to 50%, which is typically observed for Norwegian sensitive clays, the equations predict almost the same strength for OCR < 3. For higher OCR values and for *w* < 30% and *w* > 50%, such differences become more significant. This is mainly due to the different range of *m* values predicted by the two equations. Even though the m range suggested by eq. Karlsrud and Hernandez-Martinez's (2013) seems more in line with the values which are commonly observed for clays, eq. [6] resulted in slightly more accurate predictions of s_u^C for the ten test sites analysed.

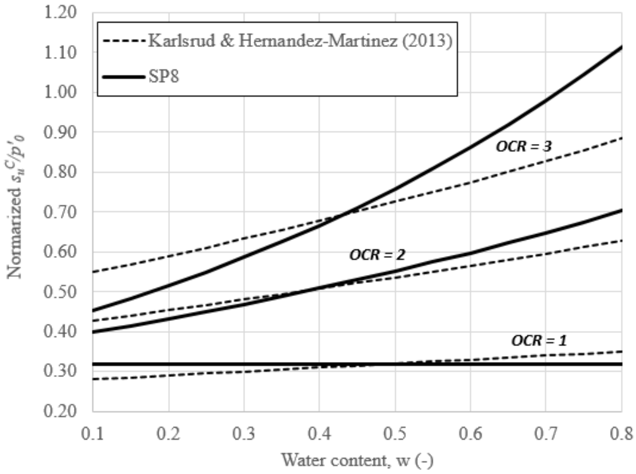

Figure 5.25 Normalized s_u^C vs water content for different OCR values.

5.11.2 Other equations recently proposed by Mayne & Peuchen (2018)

Mayne & Peuchen (2018) prepared a database study of 62 clays tested by in-situ piezocone and laboratory triaxial tests with 407 high-quality CAUC triaxial tests. Piezocone soundings with q_t, fs, and u_2 matched as same elevations at CAUC data. Five categories of soil data were studied: (a) soft-firm onshore clays; (b) soft offshore clays: (c) sensitive clays; (d) overconsolidated clays; (e) fissured clays. The following equations are proposed:

$$N_{kt} = 10.5 - 4.6 \cdot \ln(B_q + 0.1)$$

$$N_{\Delta u} = 7.9 + 6.5 \cdot \ln(B_q + 0.3)$$

$$N_{ke} = 4.5 - 10.66 \cdot \ln(B_q + 0.2)$$

The equations were applied to data from Tiller-Flotten site and the results are presented in Figure 5.26.

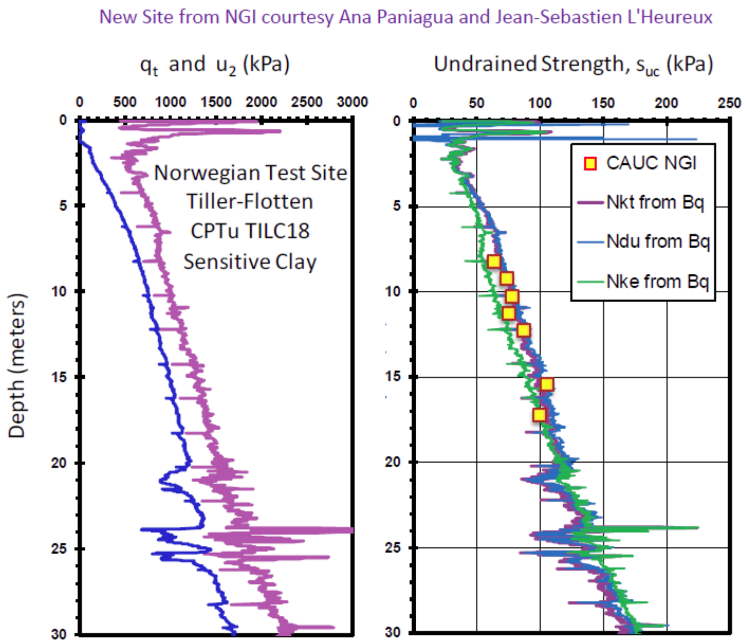

Figure 5.26 Application of Mayne & Peuchen (2018) equations to Tiller-Flotten data (Mayne & Peuchen, 2018)

6 Recommendations for engineering practice

The results and the analyses presented in this report have highlighted the difficulties in obtaining reliable correlations and modelling strength and deformation parameters from CPTU. In the Norwegian geotechnical practice, correlations by Karlsrud & Hernandez-Martinez (2013) and Karlsrud et al. (1995) are mostly used to establish engineering parameters (i.e., OCR, s_u^C from cone factors). Even though Karlsrud et al. (1995) suggested different sets of correlations for clays with $S_t < 15$ and $S_t > 15$, such a distinction could not be observed from the data presented and analysed in this study.

Moreover, in Norwegian engineering practice it is further common to use the SHANSEP method to establish the undrained shear strength profile at a given site (i.e., $s_u^C/p'_0 = S \cdot OCR^m$). A new equation (i.e. Equation [6]) proposed in this report and the ones proposed by Karlsrud et al. (1995), seemed to provide the best fit to the site-specific data from the ten sites used to evaluate the correlations, as long as the OCR and index properties (*w*, IP) profiles were properly modelled. This result agrees with the fundamental concept expressed by SHANSEP: the undrained shear strength of clays strongly depends on OCR (or p_c'), as also concluded by Larsson et al. (2007) and D'Ignazio et al. (2016) for Swedish and Finnish clays, respectively.

Given the evaluation of the equations performance in predicting actual values of undrained shear strength and OCR (and p_c') and the quantitative evaluation of r^2, the following new equations are recommended to estimate s_u^C and OCR:

i. Correlations for undrained shear strength, s_u^C:

a. $N_{ke} = 14.3 - 12.1 \cdot B_q - 2.6 \cdot log\,OCR + 0.027 \cdot IP$ *for $B_q < 1.0$* *$r^2 = 0.91$* *(4)*

$N_{ke} = 6.4 - 3.3 \cdot B_q - 2.6 \cdot log\,OCR - 0.015 \cdot IP$ *for $B_q \geq 1.0$* *$r^2 = 0.82$* *(4)*

b. $s_u^C = 0.32 \cdot p_0' \cdot OCR^{(0.20+1.17 \cdot w)}$ *$r^2 = 0.80$* *(6)*

c. $s_u^C = 0.10 \cdot q_{net}^{0.26} \cdot \Delta u^{0.74} \cdot w^{-0.26}$ *$r^2 = 0.91$* *(5)*

d. $N_{kt} = 7.95 + 0.13 \cdot IP$ *$r^2 = 0.40$* *(1)*

ii. Correlations for overconsolidation ratio, OCR:

a. $OCR = k \cdot Q_t$ *with $k = 0.44\text{-}0.47$* *(12)*

b. $OCR = 0.20 + 0.39 \cdot Q_t$ *$r^2 = 0.43$* *(14)*

c. *OCR from Original Ground Level (this equation implies curve fitting)*

d. $\sigma_p' = 2.18 \cdot q_{net}^{0.61} \cdot \Delta u^{0.54} \cdot w^{-0.65}$ *$r^2 = 0.83$* *(11)*

One should be aware that in order to estimate OCR to be used in these equations, the CPTU data should be calibrated to obtain the best fit to the inferred OCR or p_c' values from good quality oedometer test results. However, previous studies (Karlsrud & Hernandez-Martinez, 2013 and Karlsrud et al., 1995) and the new OCR correlations suggest that the determination of OCR from CPTU test is far more uncertain than the direct prediction of s_u^C from the CPTU measurements. In practice, one should estimate OCR by interpreting CPTU tests from the direct CPTU correlations, combined with estimating p_c' from what it is assumed the stress history and the present vertical effective stresses; also, by the estimated p_c' value by assessing the highest level of past sea bottom level, and a reasonable ageing factor due to creep of typically 1.3–1.5. Needless to say, the quality of the retrieved samples is the main factor that will determine the goodness of the interpretation of the CPTU data.

Despite the high quality of the samples, high scatter ($r^2 < 0.7$) was observed for some of the equations that compare cone factors and basic soil parameters. In addition to the natural variability of soil properties, another possible reason is that even though the accuracy of CPTU probes, especially in terms of the capacity to measure low values, has improved over the past decades, the results can vary among the different manufacturers (Lunne et al. 1986; Sandven, 2010; Lunne et al. 2018) this can affect the correlation results. In addition, the large variability may be due to the fact that none of the measured CPTU parameters can be expected to relate solely to s_u^C, p_c' and OCR. Stiffness of the clay as well as stress-strain relations to a level of strain of several hundred percent are likely to have an effect. There is not at present a soil model that can capture the post-peak behaviour to such large strains, and experience does not demonstrate a type of modelling that can predict this correctly. For example, the strain path method may give a reasonable picture of strain levels, but requires a soil model that can predict reliably stresses at very large strain levels. There is not even have laboratory data to cover this yet.

The correlations presented in this report should be used purely in absence of site-specific data or as a comparison tool when limited data is available. When site-specific data is available, it is further recommended to adjust the equations here proposed, by tuning the regression coefficients, to get the best estimate of OCR or p_c' and s_u^C profile. For example, equation [5] shows the highest coefficient of correlation. However, for the example presented in this report, it overestimates the measured undrained shear strength by 15%–35%.

Usually the CPTU data is used as the basis for establishing design strengths without having any laboratory tests on high quality block samples. For validation, one should compare the obtained CPTU-based engineering parameters with some empirical correlations (i.e. SHANSEP correlations provided good estimates of OCR can be obtained). When having some high quality block sample results, one will always have both odometer and triaxial and/or direct shear tests. Then, these can also be used to guide the selection of the complete strength profiles. Therefore, establishing design profiles for p_c' and s_u^C is in practice a fairly complex evaluation where engineering judgement is always needed.

In general, the equations proposed and tested in this report seem to work best for low to medium plasticity clays. For high plasticity clays, the equations including IP can still be applied, however, it is recommended to control the results by the recommended equations. In single cases, the other correlations presented in this report might also work, one should always when possible compare to good laboratory data. The correlations presented here do not substitute sampling.

Finally, with this report, the authors want to remark the importance of establishing site specific correlations when assessing geotechnical parameters from CPTU tests. In soft and sensitive clays, it is also particularly important that the correlations are established from large diameter samples of very high quality. For example, for a road project presented by L'Heureux et al. (2018), the development of empirical correlations between CPTU parameters and the undrained shear strength and the overconsolidation ratios for the clay show up to 40 % increase in undrained shear strength when compared to previously established CPTU correlations for Norwegian clays, or to correlation based on laboratory tests performed on 72 mm samples. This lead to large economic savings for the project.

7 Conclusions and recommendations for future work

This report presents the work conducted to establish correlations for engineering properties of sensitive clays from CPTU based on a high-quality block samples database of Norwegian clays. A multivariate high-quality database of sensitive clays consisting of laboratory strength and consolidation test results, index parameters and CPTU parameters was firstly established. Then, simple as well as multiple regression analyses were used to evaluate possible correlations among measured CPTU parameters (e.g. excess pore pressure, Δu, net cone resistance, q_{net}, and effective cone resistance, q_e), undrained shear strength from CAUC tests (s_u^C) and basic clay properties (e.g., OCR, plasticity, sensitivity). The target was to establish correlations characterized by high coefficient of determination (r^2). However, the final recommendation of which equations to use in practice was based on the performance of the equations in predicting high quality laboratory values of OCR and s_u^C.

Despite the goodness of the correlations established in this study, the reference dataset is still characterized by high scatter. Therefore, these correlations should be used purely in absence of site-specific data or as a comparison tool when limited data is available.

The validity of the established correlations for the engineering parameters (i.e. s_u^C and OCR or p_c') was checked for ten test sites in Norway where block samples data was available. The validation process showed that the most reliable assessment of s_u^C is achieved when using the SHANSEP framework associated with the best estimate OCR profile extrapolated from the CPTU measurements. This well reflects the strong relation that the undrained shear strength of sensitive slightly overconsolidated clays has with OCR. This has been observed for several clays around the world, including Sweden and Finland. Based on these considerations, the article addresses some practical recommendations to assess engineering parameters from CPTU and laboratory tests.

Future research work is recommended to improve further the practice of establishing strength and deformation parameters from CPTU as follows:

- Investigate the relationship between CPTU parameters, p'_c and s_u and the effective soil parameters (i.e., friction angle)
- Evaluate existing analytical solutions based on cavity expansion theory and derive improved solutions to establish engineering parameters of sensitive clays
- Collect additional high-quality laboratory data from different sites in Norway and abroad to increase both size and quality of the database and improve the correlations presented in this report
- Use Machine Learning techniques to improve predictions of soil parameters from CPTU. This will, however, require a very large database (i.e., n > 1000 data points).

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Appendix A

ANALYTICAL CPTU MODEL FOR SENSITIVE CLAY

Contents

A1 Background

A hybrid analytical model for piezocone penetration in clays was developed from Spherical Cavity Expansion (SCE) theory and Critical State Soil Mechanics (CSSM), as detailed by Mayne (1991, 2005) and Chen & Mayne (1994). The SCE-CSSM formulation provides for separate evaluations for the yield stress ratio (YSR), which is a generalized name for the overconsolidation ratio (OCR), in terms of the net cone resistance and/or the measured excess porewater pressure. For structured and sensitive clays, a slightly modified SCE-CSSM solution has recently been presented by Agaiby & Mayne (2018) and applied to fit the CPTu results with available triaxial and consolidation data from the Canadian Test Site at Gloucester, Ontario.

This modified analytical SCE-CSSM model for sensitive clays is applied to CPTu results at the Tiller-Flotten site in Norway to profile the undrained shear strength and yield stress ratio with depth. Input geoparameters include the value of friction angle at peak strength (M_{c1}) and also at large strains (M_{c2}) which correspond to the cone resistance (q_t) and measured porewater pressure (u_2), respectively. The model directly provides the value of undrained rigidity index (I_R) that depends on the slope of (u_2-σ_{vo}) versus q_{net} where $q_{net} = q_t - \sigma_{vo}$ = net cone resistance.

A similar evaluation was also done for Skatval and Koa sites.

A2 Modified SCE-CSSM for CPTu in sensitive clays

In the recent derivations, three separate algorithms relate the YSR to normalized CPTu parameters: $Q = q_{net}/\sigma_{vo}'$ and $U^* = \Delta u_2/\sigma_{vo}'$, where $q_{net} = q_t - \sigma_{vo}$ = net cone resistance. and $\Delta u_2 = u_2 - u_0$ = excess porewater pressure. These are expressed by the following:

$$YSR = 2 \cdot \left[\frac{Q/M_{c1}}{0.667 \cdot \ln(I_R) + 1.95}\right]^{1/\Lambda} \qquad [1]$$

$$YSR = 2 \cdot \left[\frac{U^* - 1}{0.667 \cdot M_{c2} \cdot \ln(I_R) - 1}\right]^{1/\Lambda} \qquad [2]$$

$$YSR = 2 \cdot \left[\frac{Q - \frac{M_{c1}}{M_{c2}} \cdot (U^* - 1)}{1.95 \cdot M_{c1} + \frac{M_{c1}}{M_{c2}}}\right]^{1/\Lambda} \qquad [3]$$

where $\Lambda = 1 - C_s/C_c$ = plastic volumetric strain potential, C_s = swelling index, C_c = virgin compression index, $I_R = G/s_u$ = rigidity index, $M_c = 6 \cdot \sin\varphi'/(3-\sin\varphi')$ = frictional parameter in q-p' space. The value of M_{c1} is defined at peak strength (i.e., φ' at q_{max}) whereas M_{c2} is the value at maximum obliquity (i.e., φ' when ratio σ_1'/σ_3' max). For insensitive clays, the value of $\Lambda = 0.80$, while for clays that are structured and/or sensitive, the value of Λ is higher, specifically: $0.9 < \Lambda < 1$.

While Eq. [1] and [2] both depend on the I_R of the clay, Eq. [3] is independent of the I_R and obtained by combination of the first two formulations.

A2.1 Undrained shear strength of clays

With regard to CPTu, the undrained shear strength of clays is most often determined using the net cone resistance:

$$s_u = q_{net}/N_{kt} \qquad [4]$$

where Nkt = cone bearing factor. In the SCE-CSSM formulation, the Vesić (1977) expression for N_{kt} is used and is given in terms of the undrained rigidity index:

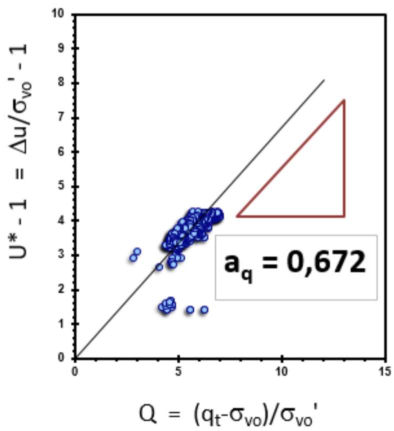
$$N_{kt} = 4/3\,[\ln(I_R) + 1] + \pi/2+1 \qquad [5]$$

A2.2 Undrained Rigidity Index

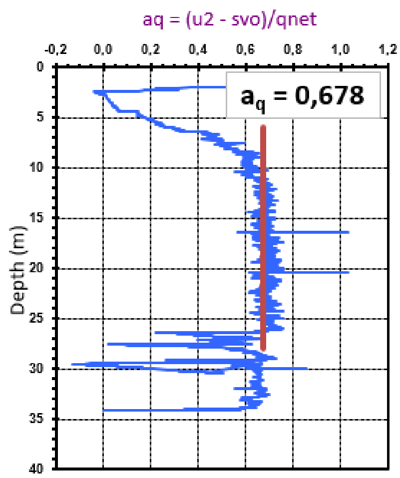
The SCE-CSSM formulation also provides the direct assessment of undrained rigidity index:

$$I_R = exp\left[\frac{1.5+2.925\cdot M_{c1}\cdot a_q}{M_{c2}-M_{c1}\cdot a_q}\right] \qquad [6]$$

where a_q is found as the ratio of $\Delta u_\sigma = u_2 - \sigma_{vo}$ to net cone resistance, q_{net}. The evaluation of a_q is determined as the slope of the graph of Δu_σ versus q_{net}, or alternatively by plotting (U*-1) versus Q as illustrated by Figure 1a which determines a value of $a_q = 0.672$ using the data from the Tiller-Flotten (TILC02) CPTu. Another means is to calculate this ratio with depth, as shown by Figure 1b.



(a)



(b)

Figure 1 Procedure to evaluate slope parameter a_q from CPTu data at Tiller-Flotten clay site.

The rigidity index depends on the undrained shear strength but at the same time I_R is used to predict undrained shear strength (or Nkt). This issue is further discussed as follows: as to the rigidity index (IR) comes directly from the SCE-CSSM solution. Just because the rigidity index is defined as ratio of shear modulus to shear strength there is no need to know s_u beforehand. I_R can sees as an operational value. For one, in SCE it really just says how big a zone of the clay goes plastic, since D/d = cube root of I_R where D = size of plastic region and d = cone diameter. Another way to think of I_R is that it is the reciprocal of the reference value of shear strain. It is our belief that this value is that taken at peak strength, q_{max}. That is the shear strain at failure (γ_s) is the reciprocal of I_R. By running a DSS it is desired to reach shear strength (s_u) at 1% strain. So this would give I_R = 100 (which is the default value taken in many numerical studies, e.g. The & Houlsby, 1991).

A3 Evaluation at Tiller-Flotten

The modified SCE-CSSM equations where evaluated at Tiller-Flotten using two CPTU profiles: TILC02 and TILC18. The results are presented in Figure 2 and Figure 3.

The Tiller-Flotten site has non-hydrostatic conditions. The sensitive clay layer, at Flotten goes from about 7-20 m depth. There is still clay under with some coarse material layers (20-33 m depth) and clay under this layer. We do not have samples after 33 m, we might use CPTU to check if the material is sensitive. The upper layer (0-7 m) is not-sensitive clay with a dry crust in the first meters.

The friction angles used for M_{c1} and M_{c2} match well with a triaxial test from 9,18 m, where a φ' at q_{max} of 30 degrees and a φ' (M.O.) of 39 degrees are obtained.

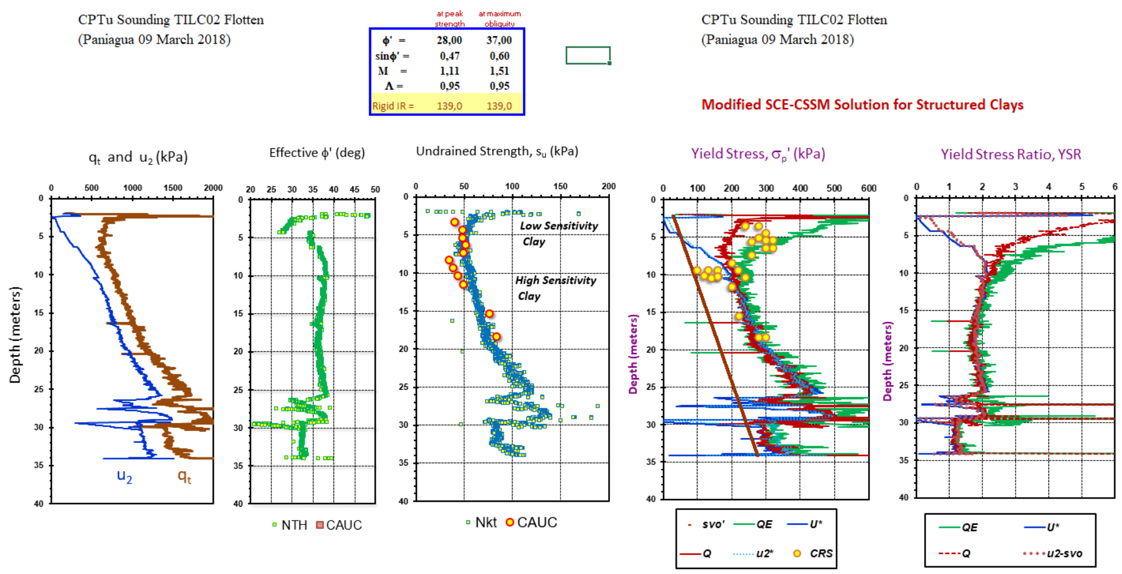


Figure 2 Results with TILC02.

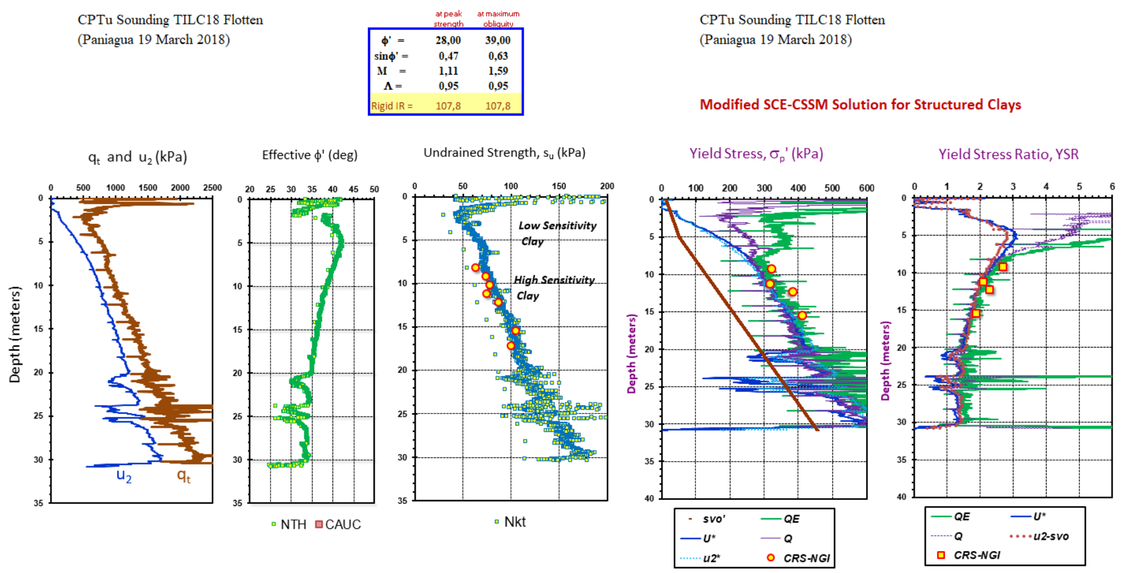


Figure 3 Results with TILC18.

A4 Evaluation at Skatval

The modified SCE-CSSM equations where evaluated at Skatval using one CPTU profile: 607-5. The results are presented in Figure 4. In Mayne's approach, the hierarchy in identification of sensitive clays is when the estimated $p_c' = 0.6\ q_E < 0.33\ q_{net} < 0.53\ \Delta u_2$. This is evident here for Skatval. For well-behaved clays like Bothkennar, all 3 equations match well). We get an I_R = 91 using M_{c1} and M_{c2} for $\varphi' = 22\,^{o}$ and 30^{o}, respectively. This gives good match with the s_{uc} but maybe under predicts for the CRS data. It seems that the CAUC and CRS may still be in the upper crust or transition to the lower softer (and more sensitive clay). In that case, maybe the unit weight drops lower in the depths from 10 to 32 m also.

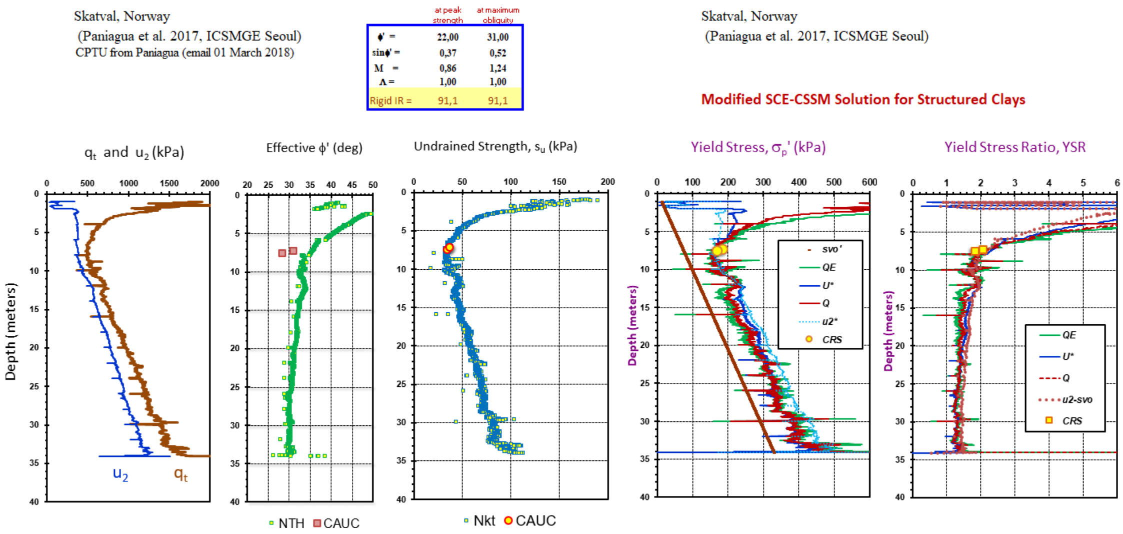


Figure 4 Results with Skatval 607-5.

A5 Evaluation at Koa

The modified SCE-CSSM equations where evaluated at Koa using one CPTU profile: 10. The results are presented in Figure 5. The evaluation for Koa site is done assuming a GWT = 1 m. In this case, a reasonable fit with M_{c1} and M_{c2} corresponding to 28 and 48 degrees, respectively, albeit the CAUC tests do not imply the latter. Also trying to match the reported range of OCRs from 2 to 4.

An alternative would be to formulate by use of paired c' and φ', in place of M_{c1} and M_{c2}. However, the I_R evaluation would be more difficult, perhaps require iteration to find. Also, c' likely tracks with σ_p' = yield stress, so adds more iterations.

The results and lab data at Koa are bit difficult to handle. At the time of sampling, it was very difficult to get the block samples. The GWT is very uncertain. Readings give very variable results and we might assume a GWT at 6 m depth. OCR values are not reliable due to the quality of the tests.

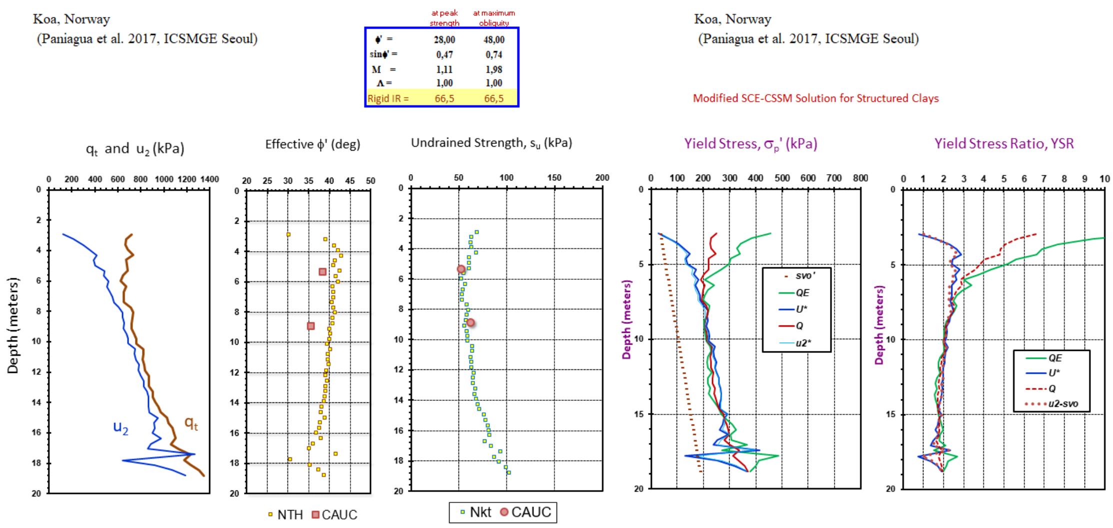


Figure 5 Results with Koa 10.

A6 References

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