Geosciences

AIMS Geosciences, 5(2): 82–103.
DOI: 10.3934/geosci.2019.2.82
Received: 19 February 2019
Accepted: 29 March 2019
Published: 26 April 2019

http://www.aimspress.com/journal/geosciences

Research article

CPTU correlations for Norwegian clays: an update

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Abstract: Geotechnical design in clay areas in Norway is mainly based on piezocone (CPTU) tests results. Strength and stiffness parameters are usually derived from CPTU parameters and empirical correlations. In order to improve geotechnical design practice (e.g. more cost-effective solutions) and to reduce risks related to the occurrence of catastrophic events (e.g. landslides, excavation failure) the Norwegian Geotechnical Institute (NGI) has recently updated its block sample database and worked on updating CPTU correlations for clays. This paper provides a short overview of NGI's block sample database consisting of 61 block samples data points collected from 17 Norwegian clay sites. Multiple regression analyses were used to evaluate possible correlations among CPTU parameters (e.g. excess pore pressure, Δu, net cone resistance, q_{net}, and effective cone resistance, q_e), undrained shear strength (s_u^C) and basic clay properties (e.g. overconsolidation ratio, OCR, plasticity, sensitivity). The target was to establish correlations characterized by low uncertainty. The most reliable assessment of undrained strength was obtained when using the Stress History and Normalized Soil Engineering Properties, SHANSEP, framework associated with the best estimate OCR profile extrapolated from the CPTU measurements. This well reflects the strong relation that s_u^C has with OCR. Despite the high quality of the samples, high scatter was observed for some of the equations that compare cone factors and basic soil parameters. In addition to the natural variability of soil properties, other possible reason to justify the scatter is that even though the accuracy of CPTU probes has improved over the past decades, especially in terms of the ability to measure low values, the results can vary among the different manufacturers. Furthermore there may be several other soil parameters than the peak undrained strength that impacts the cone resistance, for instance stiffness and large strain behavior. Such factors can affect the correlation results.

Keywords: clay; block sample; database; correlations; CPTU

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 behavior and, therefore, in more cost-effective and sustainable solutions for the construction, transport and energy sectors. There is a need for better understanding of the behavior of soft clays in order to improve geotechnical design, make it more innovative, and to reduce risks related to e.g. landslides and excavation failures.

The Norwegian Geotechnical Institute (NGI) has carried out several studies on characterization of clays and on effect of sample quality on the choice of geotechnical design parameters. In particular, the use of high-quality block samples (Ø250 mm) over the more traditional Ø54 mm or Ø72 mm samples seemed to ensure better sample quality [1–3], which is mainly reflected in the higher measured undrained shear strength (s_u^C), higher inferred preconsolidation pressure (σ_p') and higher measured soil stiffness (both drained and undrained).

Geotechnical design in clay areas in Norway is mostly based on piezocone (CPTU) test results since for example, high quality sampling can be expensive and time consuming and other field tests like field vane can be unreliable in low plasticity clays. 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 [4]. The quality of the empirical correlations is directly linked to the quality of the tests used to calibrate such models. Examples on how the use of high-quality samples resulted in improved and more cost-effective CPTU-based design are also presented in the literature [5–7]. However, the correlations presently being used in practice show large scatter and often lead to conservative choice of design parameters. There is a need for optimization of the CPTU correlations for choice of design parameters in Norwegian clays, and recommendation on the most appropriate correlations to use in practice.

1.2. Objectives and scope of work

In this work, a high-quality database of clays consisting of laboratory strength and consolidation test results, index parameters and CPTU parameters was evaluated, with the help of multiple regression analyses, to establish correlations among CPTU parameters (e.g. excess pore pressure, Δu, net cone resistance, q_{net}, and effective cone resistance, q_e), undrained shear strength from anisotropically consolidated triaxial compression CAUC tests (s_u^C) and some basic clay properties (e.g. overconsolidation ratio, OCR, plasticity).

The first part of the paper presents the collected data points and 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 established correlations are checked for specific test sites in Norway. Finally, recommendations for engineering practice are given based on the outcomes of this study.

2. CPTU database of sensitive clays

2.1. 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 [8]: changes in stress conditions, mechanical deformation, changes in water content and void ratio and 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. Long storage time can also cause sample disturbance.

The choice of sampling method strongly influences the sample quality [2,7,9–11]. Each sampling method triggers different mechanisms leading to sample disturbance as classified above. For the purpose of this study, only data obtained using the Sherbrooke block sampler [12] are considered. The Sherbrooke block sampler was developed and tested at Sherbrooke University, Quebec, Canada during the period 1975–1978 [12]. This sampler allows carving of cylindrical blocks with diameter and height of 250 mm and 350 mm respectively. 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 by using appropriate reconsolidation procedures. It has been shown that for sensitive Norwegian clays, block samples give the highest quality samples available [2].

2.2. Basic parameters considered in the database

The compiled database consists of 61 block samples data points collected from 17 sites from Norway and the well-investigated Bothkennar soft clay site [13] from UK. Some of the data have been already presented in Karlsrud & Hernandez-Martinez [3] and Karlsrud et al. [4], and exploited to derive correlations for anisotropic strength and stiffness of sensitive clays and CPTU correlations. The database has been controlled and corrected, and more recent block samples data from the soil investigation for the construction of the new highway E16, from Nybakk to Slomarka, is also included [7,14,15], in addition to block samples collected at Skatval and Koa in Trøndelag [14]. For more information and updates about NGIs block samples database the reader is referred to NGI reports [16] and [17]. 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 through a filter location in the cylindrical cone part just above conical part
- 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.
- σ_p': inferred preconsolidation stress from constant-rate-of-strain (CRS). Values are interpreted according to Karlsrud method [3,18]. Janbu method [19] was also used for σ_p' interpretation control.
- p_0': in-situ vertical effective stress
- OCR: overconsolidation ratio, = σ_p'/p_0'
- w: natural water content
- IP: plasticity index
- S_t: sensitivity measured from Fall Cone test
- Clay content

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

Table 1. Statistics of the basic parameters in the database.

Variable	n	Mean	COV
q_t (kPa)	61	644.8	0.32
q_{net} (kPa)	61	469.5	0.32
u_2 (kPa)	61	442.7	0.36
u (kPa)	61	362.7	0.38
s_u^C (kPa)	61	47.5	0.41
σ_p' (kPa)	61	209.8	0.55
p_0' (kPa)	61	96.2	0.54
OCR	61	2.4	0.52
w (%)	61	42.6	0.31
IP (%)	61	19.8	0.61
S_t	59	38.0	1.59
Clay content (%)	56	40.9	0.25

2.3. 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 [1,3,20]. 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 [21] (see Table 2).

Table 2. Criteria for sample quality after NGF [18].

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 1a 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 [22] for low plasticity clays. Despite the increasing $\Delta e/e_0$ with depth, data points fall within sample quality categories 1 and 2 (Table 2), as shown in Figure 1b (which also takes OCR into account). Therefore, the collected data points are considered of high-quality.

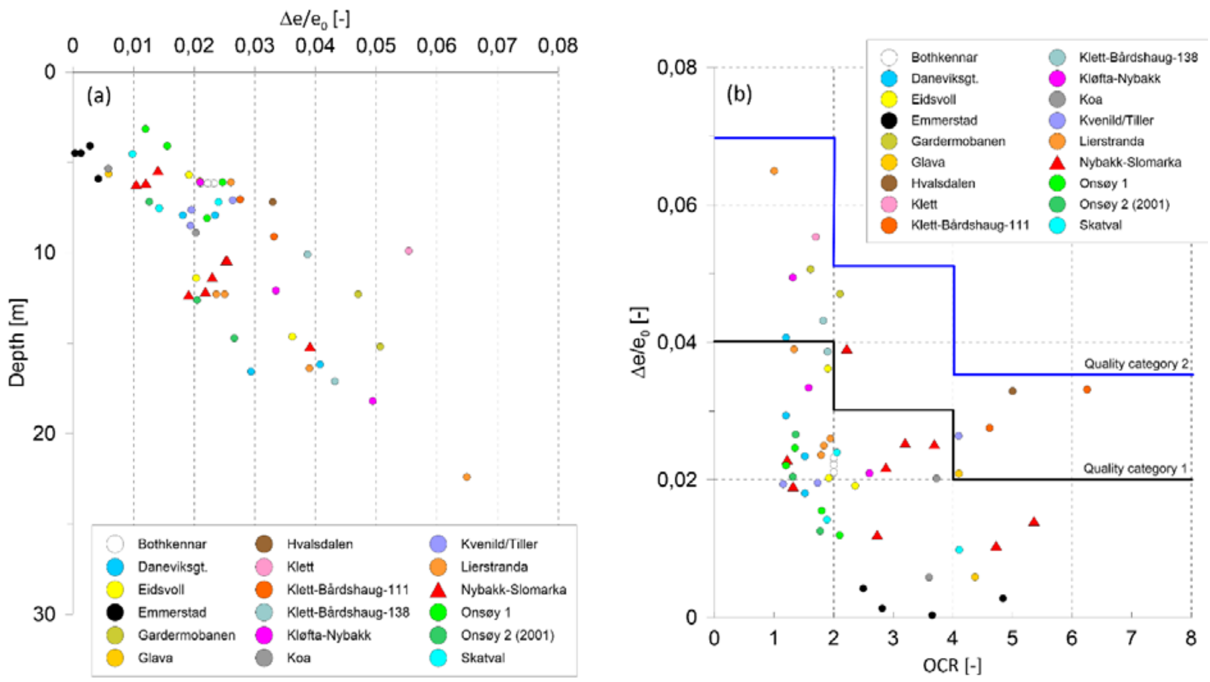

Figure 1. (a) Normalized change in void ratio ($\Delta e/e_0$) from CAUC tests on block samples versus depth for different sites. (b) Normalized change in void ratio ($\Delta e/e_0$) from CAUC tests versus over-consolidation ratio OCR for different sites.

3. CPTU results and correlations

3.1. *Definitions of CPTU factors considered*

Cone tip resistance (q_t) and excess pore pressure ($\Delta u = u_2 - u_0$) are the most frequently used parameters in CPTU correlations for undrained shear strength (s_u^C) (e.g. [4]). Based on Figure 2, the measured s_u^C seems to show lower scatter and better correlation with Δu. Different cone factors are used to correlate the measured parameters to the laboratory undrained shear strength. In this work, the reference undrained shear strength (s_u^C) is evaluated from anisotropically consolidated undrained triaxial compression tests (CAUC).

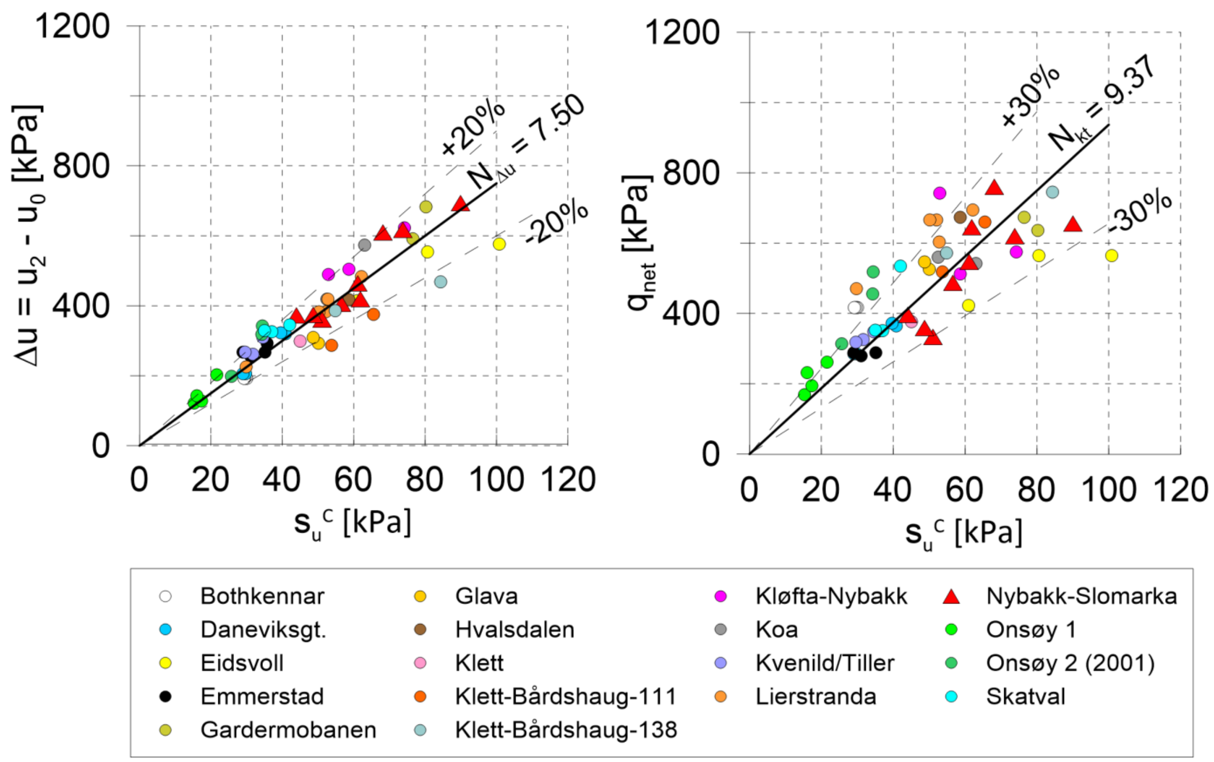

Figure 2. Excess pore pressure (Δu) and net cone resistance (q_{net}) against CAUC undrained shear strength (s_u^C).

The corrected cone resistance q_t is related to s_u^C by means of the cone factor N_{kt}, as: $N_{kt} = (q_t - p_0)/s_u^C = q_{net}/s_u^C$. The measured excess pore pressure is related to s_u^C by means of the cone factor $N_{\Delta u}$, as: $N_{\Delta u} = (u_2 - u_0)/s_u^C = \Delta u/s_u^C$. 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: $N_{ke} = (q_t - u_2)/s_u^C$. 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: $B_q = (u_2 - u_0)/(q_t - p_0)$ and $Q_t = (q_t - p_0)/p_0' = q_{net}/p_0'$.

3.2. Previous published correlations for Norwegian clays

Several authors have proposed relationships between cone factors and soil parameters (see Table 3). For instance, Karlsrud et al. [4] established CPTU correlations for undrained shear strength of Norwegian clays determined from high quality block samples only. The cone factors were grouped 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 IP. $N_{\Delta u}$ was, on the 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. [23] suggested N_{kt} to increase with increasing liquid limit and $N_{\Delta u}$ to increase with decreasing liquid limit. Low et al. [24] 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 IP, S_t, strength anisotropy and rigidity index, I_r (= G_{50}/s_u^C). No clear correlations for cone factors could be observed. These correlations stem from piston samples of unknown quality.

Regarding correlations for preconsolidation stress (σ_p') and overconsolidation ratio, OCR; various publications [25–28] propose that OCR increases when Q_t increases (i.e. increase in σ_p' when q_{net} increases). These two parameters are related by a factor *k* which is generally clay or site-specific (see Figure 6). Leroueil et al. [25] proposed for eastern Canadian clays *k = 0.28*. An average value of *k = 0.33* was recommended by Mayne [29] for φ' = 30° and rigidity index I_r = 100, with a range of 0.20–0.50. Based on 205 clay sites all over the world, Chen & Mayne [30] found an average *k = 0.31*. Powell & Lunne [28] suggested *k = 0.24* for organic soft clays and silts. The same authors [28] proposed *k = 0.25–0.40* for Onsøy, Lierstranda and Drammen clays from Norway. D'Ignazio et al. [31] proposed *k = 0.15–0.50* based on a large high-quality database of large piston and tube samples of offshore and onshore clays. A correlation between OCR and Δu was found by [28] based on data from 36 clay sites. The weakness of all but the correlations from Karlsrud et al. [4] is the unknown sample quality.

Table 3. Previous published correlations.

Variable	Correlation		Reference
s_u^C	$s_u^C = (0.27 + 0.10 \cdot w) \cdot p_0' \cdot OCR^{(0.58+0.33 \cdot w)}$	*based on SHANSEP*	[3]
N_{kt}	$N_{kt} = 7.8 + 2.5 \cdot logOCR + 0.082 \cdot IP$	$S_t < 15$	[4]
	$N_{kt} = 8.5 + 2.5 \cdot logOCR$	$S_t > 15$	[4]
	$N_{kt} = 13.4 + 6.65 w_L$		[23]
$N_{\Delta u}$	$N_{\Delta u} = 6.9 - 4.0 \cdot logOCR + 0.07 \cdot IP$	$S_t < 15$	[4]
	$N_{\Delta u} = 9.8 - 4.5 \cdot logOCR$	$S_t > 15$	[4]
	$N_{\Delta u} = 14.1 - 2.8 \cdot w_L$		[23]
N_{ke}	$N_{ke} = 11.5 - 9.05\, B_q$	$S_t < 15$ & $N_{ke,min} = 2.0$	[4]
	$N_{ke} = 12.5 - 11.0\, B_q$	$S_t > 15$ & $N_{ke,min} = 2.0$	[4]
OCR	$OCR = k \cdot Q_t$		[26]
	$OCR = (0.42\, \Delta u / p_0')^{1.35}$		[32]
	$OCR = (Q_t/a)^b$ (*a = 3, b = 1.2 for $S_t < 15$ and a = 2, b = 1.11 for $S_t > 15$*)		[4]

3.3. New correlations for undrained shear strength, s_u^C

In order to establish new and optimized correlations between undrained strength, s_u^C, and CPTU parameters, a set of multivariate regression analyses were used to evaluate the interdependence of N_{kt}, $N_{\Delta u}$, N_{ke} and clay parameters (e.g. OCR, IP, S_t). Only the relationships characterized by the highest calculated coefficient of determination (r^2) are summarized in Table 4. The value of r^2 for Eqs 5 and 7 is not shown since these equations are written after its definition (see section 3.1) and Eq 2.

Table 4. New proposed correlations for undrained shear strength, s_u^C.

Variable	Correlation	r^2	Equation number
s_u^C	$s_u^C = 0.10 \cdot q_{net}^{0.26} \cdot \Delta u^{0.74} \cdot w^{-0.26}$	*0.91*	(1)
	$s_u^C = 0.32 \cdot p_0{}' \cdot OCR^{(0.20+1.17 \cdot w)}$ *based on lab data & SHANSEP*	*0.80*	(2)
N_{kt}	$N_{kt} = 7.95 + 0.13 \cdot IP$	*0.40*	(3)
	$N_{kt} = 10.5 - 0.011 \cdot S_t$ $S_t > 30$	*0.57*	(4)
	$N_{kt} = Q_t / \left(0.32 \cdot OCR^{(0.20+1.17 \cdot w)}\right)$	-	(5)
$N_{\Delta u}$	$N_{\Delta u} = 7.50$*	*0.83*	(6)
	$N_{\Delta u} = \Delta u / \left(0.32 \cdot p_0{}' \cdot OCR^{(0.20+1.17 \cdot w)}\right)$	-	(7)
N_{ke}	$N_{ke} = 14.3 - 12.1 \cdot B_q - 2.6 \cdot \log OCR + 0.027 \cdot IP$ *for $B_q < 1.0$*	*0.91*	(8)
	$N_{ke} = 6.4 - 3.3 \cdot B_q - 2.6 \cdot \log OCR - 0.015 \cdot IP$ *for $B_q \geq 1.0$*	*0.82*	(8)

* Even though a high r^2 is obtained by multiple regression analysis, a constant cone factor with depth should not be used for further interpretation.

An attempt in defining N_{kt} or $N_{\Delta u}$ as a function of OCR was difficult since the data points show high scatter and r^2 was rather low (i.e. 0.01–0.10). 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 in Table 4, suggesting a linear dependency between N_{kt} and IP and N_{kt} and S_t (only 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 to give the highest $r^2 = 0.83$. This is remarkably higher than the r^2 for N_{kt}.

A fairly good agreement was found between N_{ke} and B_q, see Figure 3. The calculated regression line agrees with the ones proposed by Karlsrud et al. [4], accompanied by $r^2 = 0.81$. However, this approach must be carefully used, as N_{ke} is very sensitive to small changes in B_q, in particular for low values of N_{ke}. Unlike N_{kt} and $N_{\Delta u}$, N_{ke} seems also to correlate with different parameters. As shown in Table 4, N_{ke} can be linearly correlated to B_q, OCR and IP. The multivariable regression analysis resulted in a notably higher calculated r^2 than when correlating just with B_q. Karlsrud et al. [4] 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 [4] 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 Eq 8 by not more than 3%.

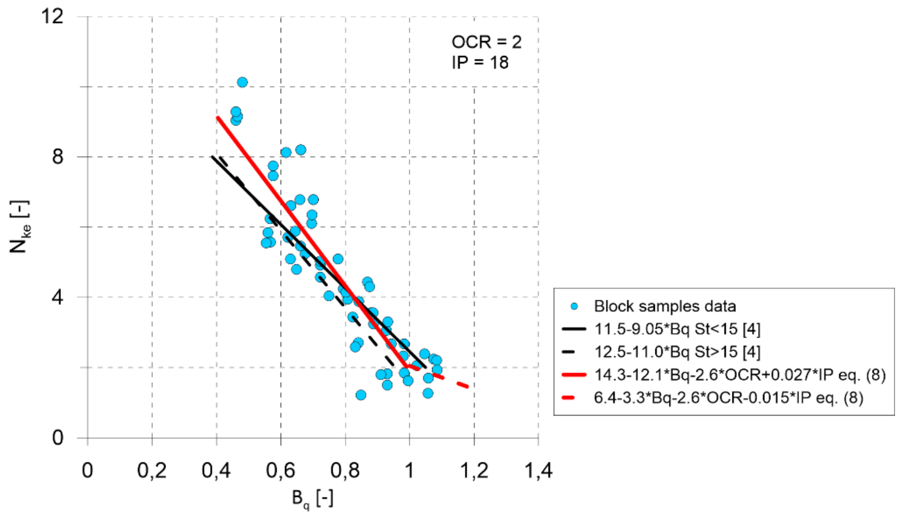

Figure 3. N_{ke} against B_q.

The dependency of cone factors on sensitivity (S_t) was also studied by Karlsrud & Hernandez-Martinez [3] and Karlsrud et al. [4], where a boundary between low sensitive and high sensitive clays at S_t = 15 was defined. No marked dependency could be observed with the updated database between $N_{\Delta u}$ or N_{ke} on S_t. On the other hand, N_{kt} seems to show a dependency on S_t for S_t > 30. For high sensitive to quick clays, N_{kt} appears to linearly decrease with increasing S_t.

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*. Results in Table 4 show a strong linear trend with r^2 close to unity.

Karlsrud & Hernandez-Martinez [3] proposed correlations for anisotropic undrained shear strength of Norwegian clays based on the Stress History and Normalized Soil Engineering Properties, SHANSEP, framework (i.e. $s_u^C/p_0' = S \cdot OCR^m$, [33]) 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 as presented in Table 3. This conclusion was based on the results of CAUC tests on samples reconsolidated to the in-situ stress state that preserved the natural OCR and soil structure.

For the database presented in this work, the best fit equation based on the SHANSEP framework is shown in Table 4 (Eq 2). Following Karlsrud & Hernandez-Martinez [3], Equation 2 reflects the results of CAUC tests reconsolidated to the in-situ state and the OCR determined from CRS tests. Given that $s_u^C = q_{net}/N_{kt}$ or $s_u^C=\Delta u/N_{\Delta u}$, one can substitute these definitions into the new equation based on SHANSEP and obtain the expression for N_{kt} (Eq 5) and $N_{\Delta u}$ (Eq 7) as shown in Table 4 as also presented by [34]. This new expression for N_{kt} will, at first glance, indicate that N_{kt} is inversely proportional to OCR. This would theoretically contradict what Karlsrud et al. [4] proposed for N_{kt}, where N_{kt} increases with increasing OCR. However, the high measured Q_t in overconsolidated soils is likely to result in higher N_{kt} at high OCR values. The theoretical trend suggested by these new relations agree with what was proposed by Karlsrud et al. [4] as presented in Figure 4: N_{kt} appears to increase with increasing OCR considering the equations only, however, he complete data set does not really show a trend. Note that the equations from Karlsrud et al. [4] are dependent on S_t while Eq 5 does not involve S_t. The values of water content and plasticity index used to evaluate the equations are equivalent in the database used in this study.

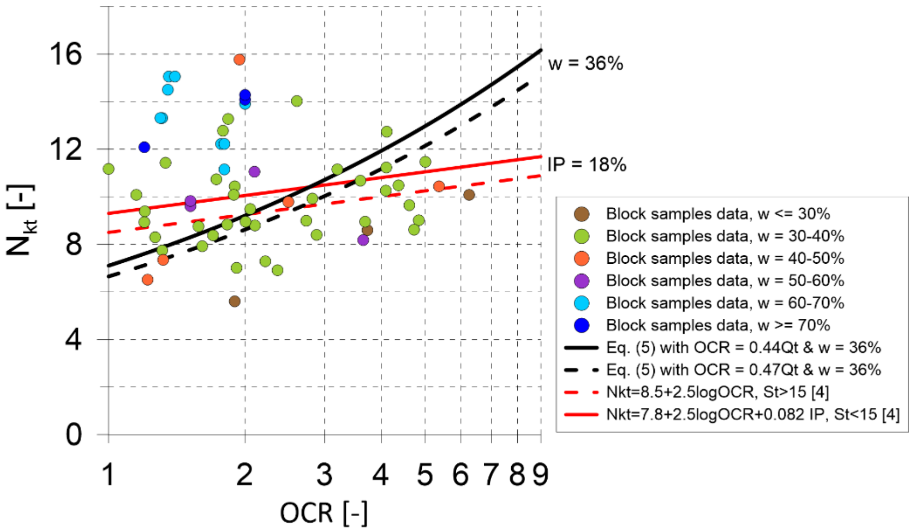

Figure 4. Variation of N_{kt} with OCR using the expressions from Karlsrud et al. [4] and Eq 5.

Figure 5 compares the expressions for $N_{\Delta u}$ proposed by Karlsrud et al. [4] and the new Eq 7 presented in Table 4 and shows that as OCR increases the value of $N_{\Delta u}$ decreases. The values of water content and plasticity index used to evaluate the equations are equivalent in the database used in this study, as well as the values of in situ vertical effective stress and excess pore pressure which at the same time are the average values presented in Table 1.

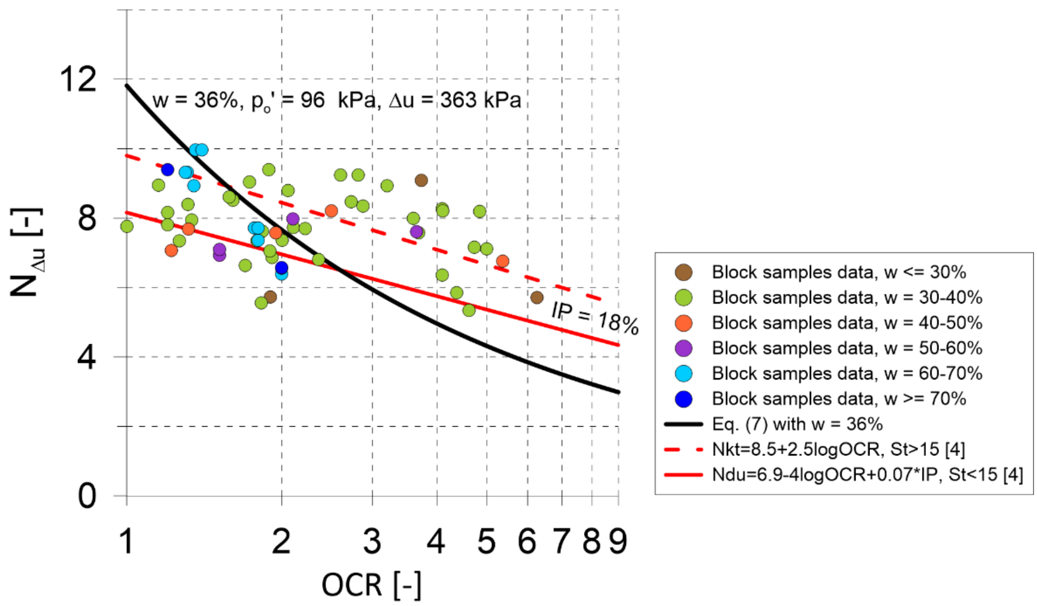

Figure 5. Variation of $N_{\Delta u}$ with OCR using the expressions from Karlsrud et al. [4] and Eq 7.

3.4. New correlations for preconsolidation stress σp' and over-consolidation ratio OCR

Correlations for preconsolidation stress (σ_p') and the overconsolidation ratio, OCR can be used both for settlement calculations and to estimate undrained shear strength. The σ_p' values in this study are often referred to as "rapid" σ_p'. In general, σ_p' from CRS oedometer tests is larger than that obtained from conventional 24-hour incrementally loaded oedometer tests (~15–30% higher) because of the higher strain rate in CRS tests [35].

A relation between σ_p' and q_{net} for Norwegian clays is shown in Table 5. When including other soil properties like, Δu and w, in a multivariable linear regression, a notable gain in r^2 is obtained (see Table 5). A similar equation as Eq 10 was found by D'Ignazio et al. [31] based on high-quality piston and tube samples of offshore and onshore clays. They found σ_p' as a function of q_{net} and Δu. However, D'Ignazio et al. [31] did not observe any notable change in the r^2 by including w in the regression analysis.

Results from the high quality database show that there indeed exists a linear dependency between Q_t and OCR. The best fit relationship obtained from this data is expressed in Table 5 and when using multivariable linear regression, the r^2 is improved by including IP in the correlation.

In general, correlations to σ_p' are characterized by higher r^2 compared to correlations to OCR. This is consistent with the findings of Chen & Mayne [30] and D'Ignazio et al. [31].

Table 5. New proposed correlations for preconsolidation stress, σ_p', and over-consolidation ratio, OCR.

Variable	Correlation	r^2	Equation number
σ'_p	$\sigma'_p = 0.04 \cdot q_{net}^{1.37}$	*0.66*	(9)
	$\sigma'_p = 2.18 \cdot q_{net}^{0.61} \cdot \Delta u^{0.54} \cdot w^{-0.65}$	*0.83*	(10)
OCR	$OCR = 0.20 + 0.39 \cdot Q_t$	*0.43*	(11)
	$OCR = 0.85 + 0.44 \cdot Q_t - 0.05 \cdot IP$	*0.63*	(12)

As part of finding new correlations, the equation $OCR = k \cdot Q_t$ from Table 3 was tested as presented in Section 4. Figure 6 shows the relation between OCR and Q_t and the range for k discussed in Section 3.2. Figure 6 suggest k ~0.2–0.75 for the present dataset, i.e. a significant scatter. Additionally, Eqs 11 and 12 are presented in Figure 6, together with the ones proposed by Karlsrud et al. [4]. As observed, Eq 11 and 12 seem to agree with the equation for clays with sensitivity S_t lower than 15 proposed by Karlsrud et al. [4].

4. Evaluation of CPTu correlations

In this section, the correlations presented in Table 4 and 5 are evaluated and validated against available s_u^C values from CAUC tests from block samples collected at 10 sites in Norway. These sites at located at Koa, Møllenberg (2 locations), Nybakk-Slomarka (3 locations), Skatval, Tiller-Flotten (2 locations) and Onsøy. However, due to space constrains, the present paper only presents results of evaluation and validation of the CPTU relationships at the Tiller-Flotten site. In addition to the evaluation of the new CPTU relationships, previously published CPTU equations (see Table 3) where included in the comparison.

4.1. Tiller-Flotten

The clay deposit at Tiller-Flotten situated close to Trondheim was selected to show how the CPTU evaluation and validation procedure was performed. This site consist of a thick deposit of low plastic clay [36]. The upper layer (0–7 m) is a non-sensitive clay with a dry crust in the first meters. From about 7.5 m below the ground surface, the clay is sensitive and quick with sensitivity up to 250. The plasticity index varies between 8 and 18, with average water content of 40%. CRS tests between 8 and 17 m depth indicate OCR = 1.8–2.9. The groundwater conditions at the site show pore pressures well below hydrostatic conditions. This is attributed to drainage of coarser layers below the clay and towards the valley river called Nidelva.

Figure 7 presents a comparison of OCR relationships at the Tiller-Flotten site. As seen on this figure, Eq 9 to Eq 11 fit well with the OCR values measured on high quality block samples before 13 m depth. After that, the equations overestimate the OCR with the exception of Eq 11. Below 8 m, the equation by Karlsrud et al. [4] overestimate the OCR values by about 32%. When using the equation $OCR = k \cdot Q_t$, the OCR from CRS tests is best captured using a $k = 0.44$. In general, for the rest of the sites a small variation of k between 0.44–0.47 was found.

Figure 7 also presents the calculation of OCR based on the Original Ground Level. This is calculated based on estimating σ_p' from what it is assumed the stress history and the present vertical effective stresses; the highest level of past sea bottom level, and a reasonable ageing factor due to creep of typically 1.3–1.5.

The OCR values measured on high quality samples were assessed by Karlsrud [18] and Janbu [19] methods. Both methods show differences for OCR values varying between 5% and 15%. Paniagua et al. [37] interpreted 129 oedometer test results by different methods and showed that, in general, the value of σ_p' and OCR, for low values of preconsolidation stress and overconsolidation ratio, does not depend on the interpretation method used when evaluating high quality samples.

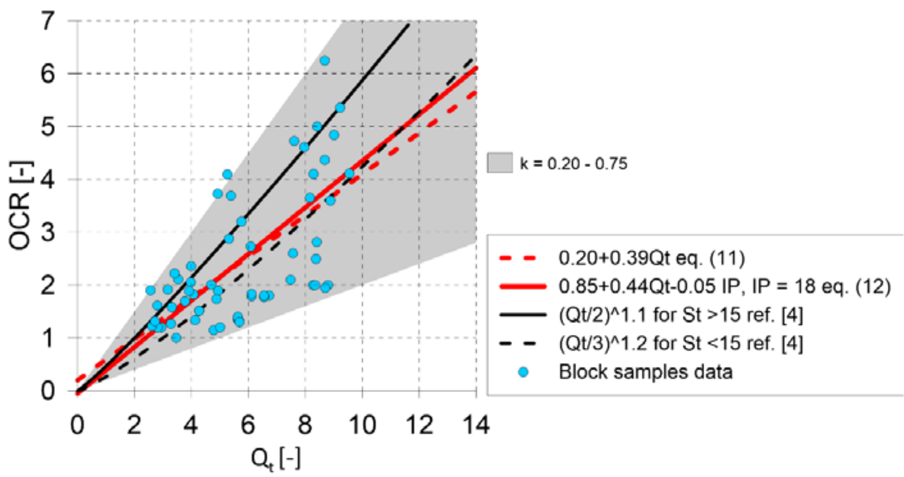

Figure 6. OCR against Q_t.

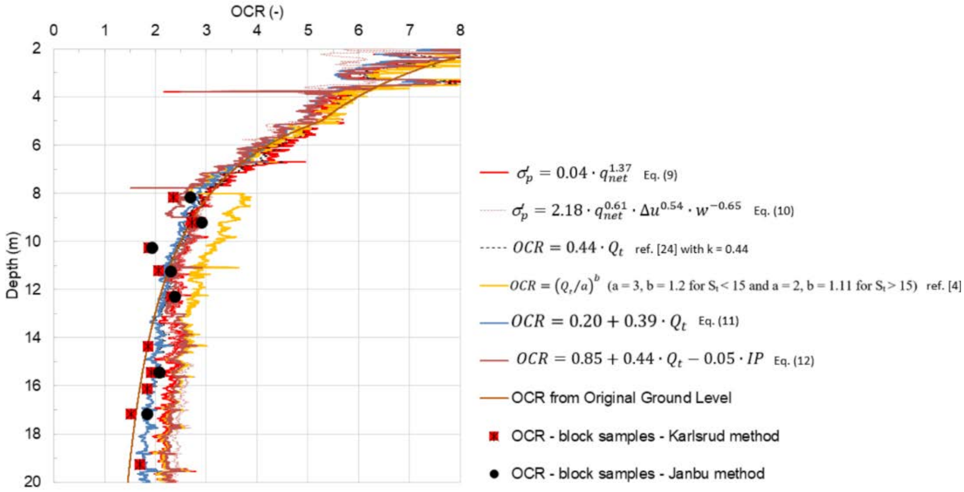

Figure 7. Application of OCR equations to CPTU data from Tiller-Flotten.

Figure 8 shows the interpreted s_u^C versus depth. CAUC tests at 10 different depths are used to evaluate the different correlations. When needed, the OCR used in the equations is taken from $OCR = k \cdot Q_t$ using k = 0.44 since this equation seems to give the best results in Figure 3. Equation 8 and the N_{kt}-equation proposed by Karlsrud et al. [4] give a good prediction of the s_u^C from the CAUC tests, even though the N_{kt}-equation proposed by Karlsrud et al. [4] uses the OCR predicted by the same authors [4] which overestimates the OCR from laboratory tests. The other equations seem to overestimate the undrained shear strength values below 7 m where the sensitive layer starts. It is interesting to note that even though Eq 1 gave the best regression coefficient r^2 in the regression analysis, this equation seems to over predict the undrained shear strength of the clay at the Tiller-Flotten site, which might be explained by the fact that Eq 1 is very sensitive to the water content values chosen as representative for the analysis.

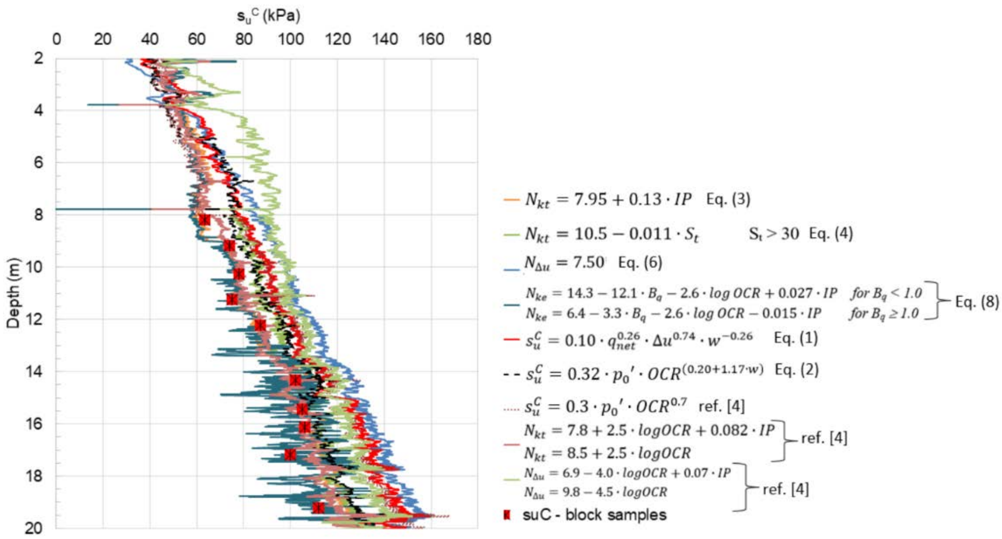

Figure 8. Application of s_u^C equations to CPTU data from Tiller-Flotten.

4.2. General equation performance for all the sites

Similar to the Tiller-Flotten comparison assessment presented above, the equations in Tables 3, 4 and 5 were tested on 10 other well-documented Norwegian clay sites, see [17]. The performance of the equations was evaluated by computing how far the predictions were from the laboratory values of OCR and s_u^C. In total, more than 35 data points were evaluated and the results were divided into three categories (i.e. >20%, 10–20% and <10%). The final recommendations are based on how good the equation performed in this evaluation. Tables 6 and 7 show a summary of the accuracy in the prediction of OCR and s_u^C with the different equations. For the OCR evaluation, Table 6 shows that OCR is best evaluated using $OCR = k \cdot Q_t$ with k = 0.44–0.47. For the undrained shear strength the N_{ke} correlation by Eq 8 seems to give the best prediction followed by the N_{kt} correlation by Eq 3. The accuracy of the equations showing "the best fit" are, nevertheless, dependent upon the reliability of the modelled OCR, water content and plasticity index profile.

Table 6. Summary of the accuracy in the prediction of OCR with the different equations at 10 different test sites.

Equation		Prediction < Actual		Prediction ~ Actual	Prediction > Actual	
		> 20%	10%–20%	±10%	10%–20%	> 20%
(9)	$\sigma_p' = 0.04 \cdot q_{net}^{1.37}$	34%	9%	23%	11%	23%
(10)	$\sigma_p' = 2.18 \cdot q_{net}^{0.61} \cdot \Delta u^{0.54} \cdot w^{-0.65}$	6%	9%	43%	20%	23%
[26]	$OCR = k \cdot Q_t$ with k = 0.44-0.47	3%	9%	60%	20%	9%
(11)	$OCR = 0.20 + 0.39 \cdot Q_t$	20%	3%	46%	17%	14%
(12)	$OCR = 0.85 + 0.44 \cdot Q_t - 0.05 \cdot IP$	26%	17%	23%	9%	26%
(-)	OCR from Original Ground Level	20%	17%	46%	11%	6%

Table 7. Summary of the accuracy in the prediction of s_u^C with the different equations at 10 different test sites. OCR values used in equations build as function OCR were taken from $OCR = k \cdot Q_t$ in all cases.

Equation		Prediction < Actual		Prediction ~ Actual	Prediction > Actual	
		> 20%	10%–20%	±10%	10%–20%	> 20%
(1)	$s_u^C = 0.10 \cdot q_{net}^{0.26} \cdot \Delta u^{0.74} \cdot w^{-0.26}$	0%	13%	42%	18%	26%
(2)	$s_u^C = 0.32 \cdot p_0{}' \cdot OCR^{(0.20+1.17 \cdot w)}$	0%	3%	55%	26%	16%
(3)	$N_{kt} = 7.95 + 0.13 \cdot IP$	18%	13%	53%	13%	3%
(4)	$N_{kt} = 10.5 - 0.011 \cdot S_t$ $S_t > 30$	5%	5%	30%	50%	10%
(6)	$N_{\Delta u} = 7.50$	3%	3%	37%	29%	29%
(8)	$N_{ke} = 14.3 - 12.1 \cdot B_q - 2.6 \cdot log\, OCR + 0.027 \cdot IP$ $N_{ke} = 6.4 - 3.3 \cdot B_q - 2.6 \cdot log\, OCR - 0.015 \cdot IP$	5%	24%	58%	5%	8%

The performance of Eqs 5 and 7 was evaluated by comparing the measured versus the calculated N_{kt} values from Eq 5 and $N_{\Delta u}$ values from Eq 7, respectively, as presented in Figures 9 and 10. The OCR values are obtained from laboratory data by either [18] or [19] methods. Measured and calculated data points agree relatively well. This is an expected result considering that for this specific case: i) some of the input values in the database appear on both the measured and the calculated N_{kt} and $N_{\Delta u}$, and ii) some of the data points contained in the database were already exploited by Karlsrud & Hernandez-Martinez [3] to derive the equations evaluated. Even though, predicted N_{kt} and $N_{\Delta u}$ values differ from measured N_{kt} and $N_{\Delta u}$, respectively, mostly within a range of ±10%.

Figure 11 shows a comparison between measured s_u^C values and calculated s_u^C values from Eq 1, which is a direct correlation from CPTU parameters. Most of the values are within a range of ±20% difference. There is a slight tendency that the predicted s_u^C from Eq 1 might give higher s_u^C than the actual measured s_u^C in about 0–20%.

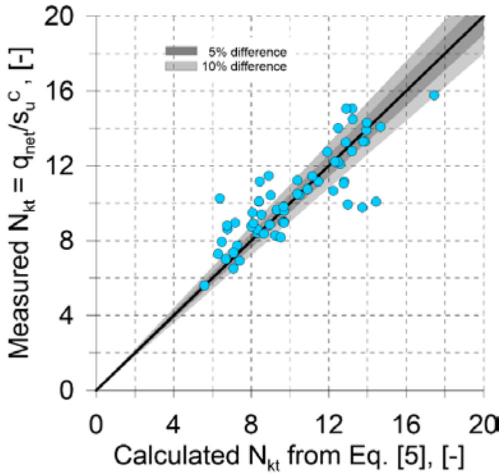

Figure 9. Measured N_{kt} against calculated from Eq 5.

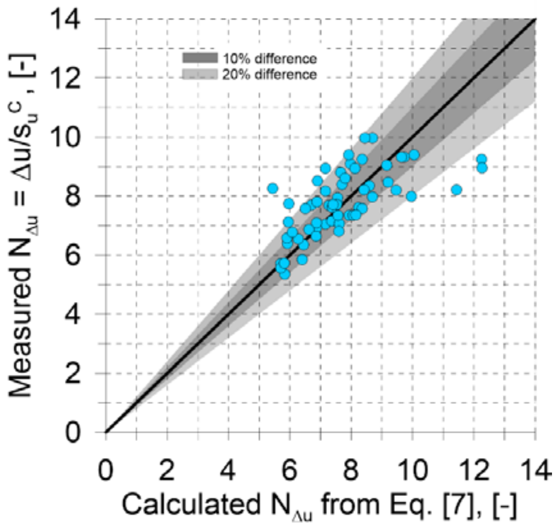

Figure 10. Measured $N_{\Delta u}$ against calculated from Eq 7.

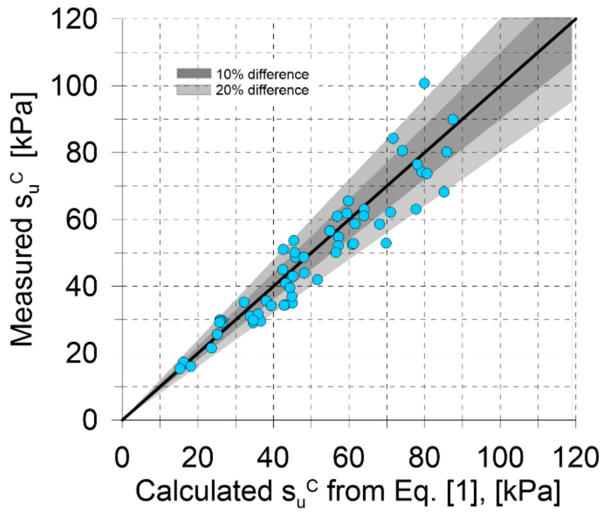

Figure 11. Measured s_u^C against calculated from Eq 1.

4.3. Comparison between SHANSEP based equations

Comparing both SHANSEP based equations (i.e., $s_u^C/p'_0 = S \cdot OCR^m$), one observes that for an OCR of 1, the equation by Karlsrud & Hernandez-Martinez [3] shown in Table 3, suggests that the normalized strength (s_u^C/p_0') increases with increasing water content, while *S* is constant and equal to 0.32 according to the new proposed Eq 2, similar to one presented by DeGroot [34]. Larsson et al. [23] suggested *S* = 0.33 (constant) for triaxial compression strength of Swedish clays. Also, the SHANSEP exponent *m* varies between 0.6 and 0.85 according to Karlsrud & Hernandez-Martinez [3], while *m* = 0.35–1.15 from the equation proposed herein; for *w* = 10–80%. The same authors [23] suggested *m* = 0.8 for Swedish clays. D'Ignazio et al. [38] reported *m* ≈ 0.76 for Finnish clays, independent of any index parameters. In general, it is not straightforward to explain the directly proportional relationship between $s_u^C/\ p_0'$ and water content without speculating on structure and mineralogy of sensitive clays. This is, however, beyond the scope of this study. From a purely statistical point of view, the present dataset suggest a strong linear correlation between $s_u^C/\ p_0'$ and water content.

Figure 12 presents the normalized s_u^C against OCR for different water contents as well as the lines proposed by Karlsrud et al. [4]. Both approaches are pretty similar, and for water contents varying between 30 to 50%, the previous equations proposed by Karlsrud et al. [4] give a lower and upper bound to the SHANSEP based equation presented in this paper. Figure 12 also illustrates that 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 Karlsrud & Hernandez-Martinez [3] seems more in line with the values which are commonly observed for clays, the new proposed equation resulted in slightly more accurate predictions of s_u^C for the ten test sites analyzed.

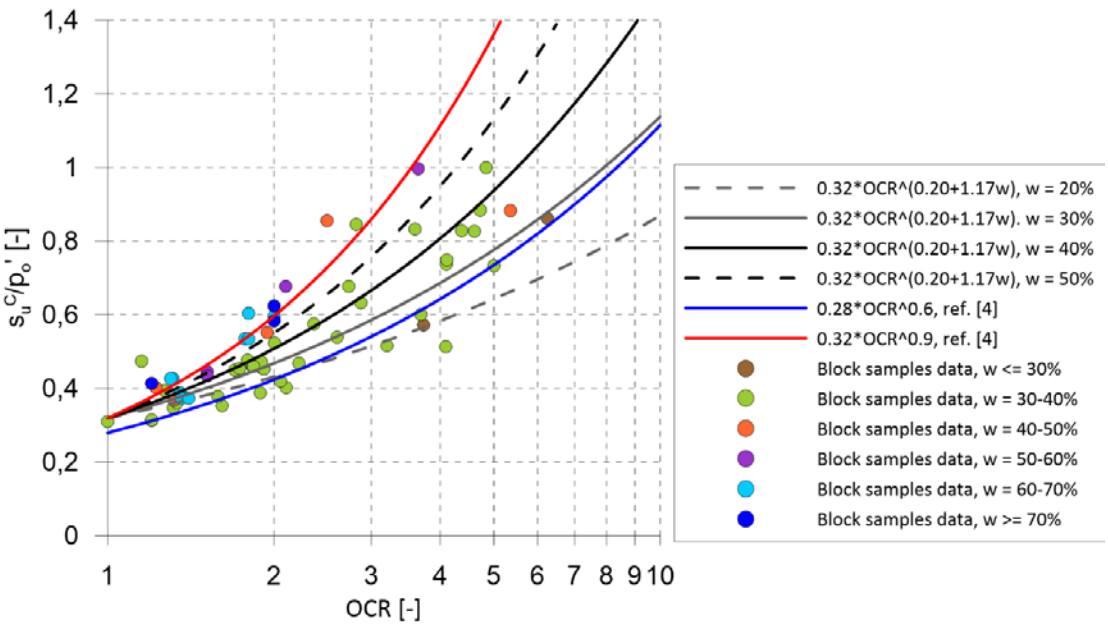

Figure 12. Normalized s_u^C against OCR values.

5. Recommendations for engineering practice

The results and the analyses presented in this paper 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 [3] and Karlsrud et al. [4] are mostly used to establish engineering parameters (i.e., OCR, s_u^C from cone factors). Even though Karlsrud et al. [4] 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 analyzed 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. Eq 2) proposed in this paper and the ones proposed by Karlsrud et al. [4] 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 σ_p'), as also concluded by Larsson et al. [23] and D'Ignazio et al. [38] for Swedish and Finnish clays, respectively.

Given the evaluation of the equations performance in predicting actual values of undrained shear strength and OCR (and σ_p') 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* $B_q < 1.0$ $r^2 = 0.91$ (8)

$N_{ke} = 6.4 - 3.3 \cdot B_q - 2.6 \cdot log\,OCR - 0.015 \cdot IP$ *for* $B_q \geq 1.0$ $r^2 = 0.82$ (8)

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

c. $s_u^C = 0.10 \cdot q_{net}^{0.26} \cdot \Delta u^{0.74} \cdot w^{-0.26}$ *r^2 = 0.91* (1)

d. $N_{kt} = 7.95 + 0.13 \cdot IP$ *r^2 = 0.40* (3)

ii. Correlations for overconsolidation ratio, OCR:

a. $OCR = k \cdot Q_t$ *with k = 0.44-0.47 (this equation implies curve fitting)* [24]

b. $OCR = 0.20 + 0.39 \cdot Q_t$ *r^2 = 0.43* (11)

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* (10)

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 σ_p' values from good quality oedometer test results. However, previous studies [3,4] 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 σ_p' from what it is assumed the stress history and the present vertical effective stresses; also, by the estimated σ_p' 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 [39–41]; 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, σ_p' 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 paper 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 σ_p' and s_u^C profile. For example, Eq 1 shows the highest coefficient of correlation. However, for the example presented in this paper, 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 σ_p' 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 paper 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 paper might also work, one should always when possible compare to good laboratory data. The correlations presented here do not substitute sampling.

Finally, with this paper, 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 [7], 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.

6. Conclusions

This paper 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 σ_p') 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.

Conflict of interest

The authors declare no conflict of interest.

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