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Research article

Estimation of preconsolidation stress of clays from piezocone by means of high-quality calibration data

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Abstract: An extensive database of high-quality piezocone (CPTU) and laboratory oedometer test data on onshore and offshore clays worldwide has been established. The database covers a wide range of index parameters and overconsolidation ratios (*OCR*) in the range 1 to 5. The purpose is to derive general correlations to model preconsolidation stress in clays from CPTU data based on high-quality laboratory data. Several studies have already discussed such correlations for different clay types, where the preconsolidation stress is defined as a function of the cone resistance and/or the pore pressure measured in CPTU tests. Often, these correlations are characterized by high uncertainty, mainly because of the sample quality of the laboratory data. New correlations are proposed based on the new database. These correlations are meant to be used for preliminary assessment of preconsolidation stress in the absence of laboratory data or as a comparison tool when limited test data is available.

Keywords: preconsolidation stress; *OCR*; CPTU; correlation; clay

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1. Introduction

The preconsolidation stress, or yield stress, σ'_p is a fundamental and one of the most relevant engineering parameters of clays. The preconsolidation stress represents the maximum vertical effective overburden stress that the soil has experienced, and is used to define the stress history of the soil by means of the overconsolidation ratio *OCR* (=σ'_p/σ'_v, where σ'_v is the present vertical effective stress). The overconsolidation in the soil is often the result of mechanical unloading (i.e., ice melting or removal of soil) or cementation of the soil skeleton due to aging phenomena or chemical reactions occurring in the soil under some favorable conditions [1]. Furthermore, σ'_p and OCR strongly correlate with the undrained shear strength of clays [1–4].

The preconsolidation stress σ'_p is commonly determined from laboratory constant-rate-of-strain (CRS) or incrementally loaded (IL) oedometer tests and is generally affected by the quality of the tested sample [5–8], test procedures and the chosen interpretation method [9]. In-situ tests such as the piezocone test (CPTU) are also used in practice to evaluate σ'_p or OCR, with the advantage of providing continuous measurements with depth. The CPTU test requires, however, laboratory test results for a proper calibration. In absence of site-specific calibration data, σ'_p and OCR can be estimated from available correlations. Several authors have discussed the interpretation of σ'_p from piezocone for different soil types and proposed models that correlate σ'_p and OCR with the CPTU parameters [10–15]. Often, these models are calibrated for a specific soil type [14] or are characterized by high scatter around the observed trends [13]. One of the uncertainties that lies behind the literature correlations is the quality of the samples used to derive them. Sample quality is seldom discussed in these studies.

The scope of this study is to evaluate CPTU-based correlations for σ'_p and OCR based on high-quality data. To do that, a multivariate database consisting of 249 high-quality clay data points covering onshore and offshore clays worldwide has been established. The database covers a wide range of plasticity, with plasticity index I_p varying between 16 and 110%, water content w between 25 and 140% and sensitivity S_t between 1 and 100, with OCR values ranging from 1 to 5 (normally to medium over-consolidated clays). Sampling depths range between 1 and 35 m. The existing large CLAY/10/7490 database by Ching and Phoon [16] is used for comparison and validation of the trends observed from the compiled high-quality database.

2. Multivariate CLAY/9/249 clay database

The compiled database consists of the following nine dimensionless parameters:

1. Preconsolidation stress σ'_p/p_a
2. Total vertical stress σ_v/p_a
3. Effective vertical stress σ'_v/p_a
4. Corrected cone tip resistance q_t/p_a
5. Pore pressure measured above the cone u_2/p_a
6. Static in situ pore pressure u_0/p_a
7. Plasticity index I_p
8. Natural water content w
9. Sensitivity S_t

where p_a is the atmospheric pressure (p_a~100 kPa).

The multivariate database contains n = 249 clay data points. Full multivariate data is available for all the parameters, except for I_p and S_t. The database is labeled as CLAY/9/249, based on the notation (soil type)/(number of parameters of interest)/(number of data points) proposed by Ching and Phoon [16].

Table 1 shows the basic statistics of the CLAY/9/249 database, while Table 2 summarizes the basic properties of each site considered in this study. The inferred σ'_p values refer to CRS oedometer tests, while S_t was measured from Fall Cone tests. The σ'_p values in this study can be referred to as “rapid” σ'_p. Several studies have shown that σ'_p from CRS oedometer tests is much larger than that obtained from conventional IL tests (~15–30% higher) with 24-hour load steps because of the higher strain rate in CRS tests [17].

Table 1. Basic statistics of CLAY/9/249 database.

Parameter	σ'_p/p_a	σ_v/p_a	σ'_v/p_a	q_t/p_a	u_2/p_a	u_0/p_a	I_p (%)	w (%)	S_t (-)
n	249	249	249	249	249	249	158	249	152
Mean	0.67	1.08	0.42	3.84	2.22	0.66	40.40	81.90	22.30
COV	0.69	0.78	0.77	0.67	0.66	0.81	0.38	0.39	1.20
Min	0.12	0.20	0.06	0.66	0.39	0.10	14.00	25.00	1.10
Max	2.80	5.83	2.30	15.00	9.40	3.53	109.9	179.80	99.40

*COV = coefficient of variation

Table 2. Summary of basic properties of the different sites in CLAY/9/249 database.

Site	n	Type	w (%)	I_p (%)	S_t (-)	OCR	$\Delta e/e_0$
Barents Sea	36	Offshore	25–48	22–42	1.4–2.7	1.2–4.5	0.006–0.062
Bothkennar	2	Onshore	69–70	42–49	8–10	1.9	0.022–0.023
Egypt, Site 1	10	Offshore	109–161	56–69	2.5–5.2	1.2–1.7	0.019–0.054
Egypt, Site 2	6	Offshore	111–138	62–72	3.3–6.2	1.3–2.1	0.03–0.05
Egypt, Site 3	9	Offshore	80–180	32–57	3.1–6.0	1.2–2.1	0.024–0.06
Finland, Site 1	7	Onshore	63–119	39–59	18.1–21.5	1.2–2.0	0.024–0.059
Finland, Site 2	20	Onshore	56–112	16–36	66–99	1.3–1.8	0.021–0.047
Finland, Site 3	38	Onshore	71–111	21–41	33–72	1.3–2.7	0.02–0.059
Finland, Site 4	18	Onshore	87–118	36–58	16–45	1.4–2.4	0.021–0.065
Gulf of Guineas	20	Offshore	79–147	64–110	n/a	1.4–3.5	0.016–0.055
Indian Coast	15	Offshore	48–126	34–68	1.1–5.5	1.3–2.7	0.008–0.054
Lierstranda, Norway	3	Onshore	33–39	14–19	8–12	1.1–1.9	0.025–0.065
Norwegian Sea	3	Offshore	118–130	38–63	6.5–7.3	1.3–1.4	0.052–0.058
Norwegian trench, Site 1	6	Offshore	27–67	22–41	2.5–6.2	1.6–2.3	0.01–0.047
Norwegian trench, Site 2	22	Offshore	55–84	27–43	3.6–8.0	1.1–2.5	0.016–0.066
Norwegian trench, Site 3	5	Offshore	59–75	34–41	3.6–6.0	1.6–2.6	0.012–0.03
Onsøy, Norway	4	Onshore	43–72	24–44	10–12	1.2–1.6	0.049
Vøring basin, Norway	25	Offshore	42–89	30–48	2.1–5.6	1.1–1.8	0.025–0.068

The offshore data and the data for three onshore sites (two in Norway, one in UK) is collected from projects carried out by the Norwegian Geotechnical Institute (NGI). Offshore data is obtained from 75 mm diameter piston sampler, while the 250 mm diameter Sherbrooke block sampler [18] was used at Onsøy, Lierstranda and Bothkennar sites. The NGI data is discussed in Yang et al. [19]. For these data, σ'_p was interpreted according to the method by Casagrande [20].

The majority of the data from Finland is extracted from [7], while additional data was provided by the Laboratory of Earth and Foundation Structures of Tampere University. The Finland data is mainly based on a large 132 mm diameter tube sampler [8]. The interpretation of σ'_p was based on a method that is commonly used in Finland, where the Janbu constrained modulus [21] is fitted to the

CRS stress-strain curve using the least square method for given stress ranges in the pre- and post-yielding regions. The σ'_p is then determined from the intersection of these lines [22]. This gives very consistent σ'_p values for high quality samples of sensitive clays, which would be very close to the ones by Casagrande's method.

Overall, the data contained in the CLAY/9/249 database is to be considered of high-quality, since samples were retrieved using samplers of higher diameter than the standard 50 mm piston or tube sampler. In general, high quality can be expected when using large diameter sampler, provided a favorable geometry of sample tube and cutting shoe [6].

Sample quality was assessed by means of the well-known criterion proposed by Lunne et al. [5]. This criterion considers the volume change during recompression to the in-situ stress ($\Delta e/e_0$, where e is the void ratio) and the OCR. The range of $\Delta e/e_0$ values in Table 2 is 0.006–0.068. Figure 1 shows the variation of $\Delta e/e_0$ with OCR and depth. In general, there is a tendency of $\Delta e/e_0$ to increase with depth. According to Figure 1, the data points in the CLAY/9/249 database fall into the "Very good to excellent" and “Good to fair” sample quality categories, except for four data points that lie on boundary between “Good to fair” and “Poor” quality.

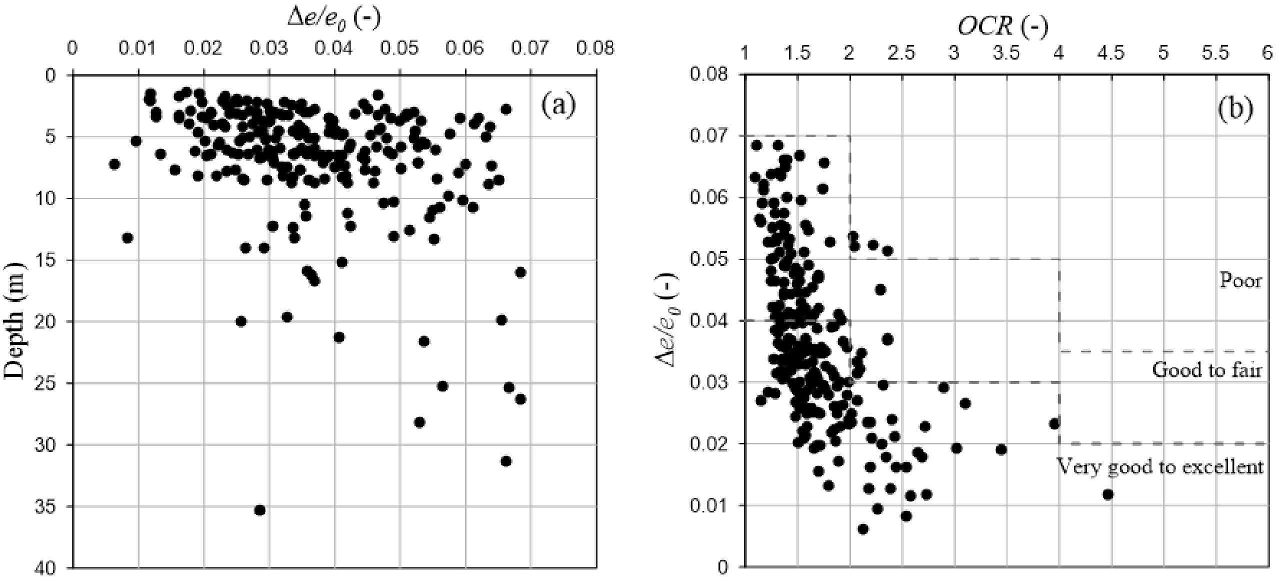

Figure 1. (a) $\Delta e/e_0$ versus depth and (b) $\Delta e/e_0$ versus OCR.

3. Review of existing CPTU-based correlations for σ'_p and *OCR* and comparison with CLAY/9/249 database

Often, engineering properties are derived from normalized CPTU parameters, besides the standard measured parameters. Among these, the most common are:

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

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

A number of theoretical and empirical correlations to model OCR or σ'_p from CPTU parameters have been proposed in the geotechnical literature. These include correlations between OCR and B_q [13,23], OCR and Q_t [11,24], OCR and Q_u [12], OCR and Q_e [10,13], σ'_p and q_{net}, Δu and q_e [13,15,25,26].

While the majority of the studies in the literature attempted to empirically correlate σ'_p and OCR to piezocone parameters, some authors made theoretical evaluations to rationally link these parameters. For instance, Konrad and Law [27] derived an analytical expression to evaluate σ'_p during cone penetration based on measured piezocone parameters, effective strength parameters and cone roughness. Some authors [11,12,15] combined Spherical Cavity Expansion theory and Critical State Soil Mechanics concepts to link OCR with normalized CPTU parameters. The link between OCR and CPTU parameters can be further explained by the strong relation that exists between OCR and undrained shear strength of clays s_u, as suggested by the SHANSEP approach [2]. As the s_u is linked to the CPTU parameters by a bearing capacity theory, it is logical to relate OCR to the same parameters, as suggested by e.g. [28].

In general, published literature correlations follow the format represented by Eq 1 as follows:

$$Y_i = k_j X_j^{\alpha_j} \tag{1}$$

where $Y_i = \{Y_1, Y_2\} = \{\sigma'_p, OCR\}$, $X_j = \{X_1,\ldots, X_7\}$ are the measured or derived CPTU parameters and k_j, α_j the regression coefficients relative to the different parameters as described in Table 3. Table 3 summarizes typical values of k_j and α_j from the literature for different types of correlations.

Powell et al. [24] concluded that the linear relationship ($\alpha_j = 1$) between σ'_p and q_{net} or OCR and Q_t seems to be the most reliable. They observed k_1 (or k_4) to be clay or site-dependent and measured values between 0.2 and 0.5 for normally to medium overconsolidated clays ($OCR < 5$). Based on a large data set consisting of 205 clay sites all over the world, Chen and Mayne [13] suggested $k_1 = 0.31$ with a coefficient of determination $r^2 = 0.82$. They further observed how correlations to σ'_p resulted in higher r^2 compared to correlations to OCR. For Eastern Canada clays, Leroueil et al. [25] proposed $k_1 = 0.28$. For organic soft clays and silts, Mesri [26] recommended $k_1 = 0.24$. Mayne [15] proposed $k_1 = 0.33$ for clays with $OCR < 3$, based on an analytical solution that combines Spherical Cavity Expansion theory and Critical State Soil Mechanics. Mayne and Holz [12] further observed that a good non-linear correlation existed between OCR and Q_u. Moreover, Chen and Mayne [13] and Schroeder et al. [23] suggested OCR to be dependent on B_q, decreasing with increasing B_q.

Figures 2 and 3 show a comparison between the CLAY/9/249 database and some of the existing correlations for σ'_p and OCR respectively. The uncertainties of the existing correlations associated with the CLAY/9/249 database are evaluated by calculating the bias factor (b) and coefficient of variation (COV) according to Ching and Phoon [16]. The bias factor b is defined as the mean value of the ratio (measured OCR)/(calculated OCR) or (measured σ'_p)/(calculated σ'_p). If $b = 1$, the prediction is unbiased. The COV is calculated as the ratio of the standard deviation of the (measured OCR)/(calculated OCR) ratio and the bias factor b. If COV tends to zero, low variability is expected around the mean trend of the data. Calculated b and COV for the existing correlations in Figures 2 and 3 are summarized in Table 4.

Table 3. Literature summary of calibration parameters for σ'_p and OCR from Eq 1.

Target parameter (Y_i)		CPTU parameter (X_j)		Coefficient k_j		Coefficient α_j		Source
Y_1	σ'_p	X_1	q_{net}	k_1	0.24–0.40	α_1	1.0	[13,25,29]
Y_1	σ'_p	X_2	Δu	k_2	0.53–0.54	α_2	1.0	[13,15]
Y_1	σ'_p	X_3	q_e	k_3	0.50–0.60	α_3	1.0	[13,15]
Y_2	OCR	X_4	Q_t	k_4	0.20–0.50	α_4	1.0–1.2	[14,24]
Y_2	OCR	X_5	Q_u	k_5	0.31	α_5	1.35	[12]
Y_2	OCR	X_6	Q_e	k_6	0.5–0.545	α_6	0.97–1.0	[10,13]
Y_2	OCR	X_7	B_q	k_7	0.63–1.026	α_7	−1.077/−1.286	[13,23]

According to Table 4, all the correlations seem to overpredict the mean trend of the data in CLAY/9/249, except for the expression by Schroeder et al. [23], which underpredicts the mean trend. In particular, the correlations by Chen and Mayne [13] for σ'_p seem to capture the upper boundary of the data points in CLAY/9/249, as shown in Figure 2. The existing $Q_t - OCR$ and $Q_e - OCR$ correlations seem to deviate significantly from the mean trend of the data points. On the other hand, the $Q_u - OCR$ and $B_q - OCR$ relations by Mayne and Holtz [12] and Chen and Mayne [13], respectively, appear to better fit the data trend in CLAY/9/249. Overall, the linear $q_{net} - \sigma'_p$ and $Q_t - OCR$ relations seem to be characterized by the lowest uncertainties (lowest COV = 0.20 in Table 4). This is in line with the experimental observations by Powell et al. [24].

Table 4. Bias and uncertainties of the existing correlations associated with CLAY/9/249 database.

Correlation	Source	b	COV
$\sigma'_p = 0.305q_{net}$	Chen and Mayne [13]	0.80	0.20
$\sigma'_p = 0.53\Delta u$	Chen and Mayne [13]	0.81	0.22
$\sigma'_p = 0.50q_e$	Chen and Mayne [13]	0.92	0.35
$OCR = 0.317Q_t$	Chen and Mayne [13]	0.77	0.20
$OCR = 0.259Q_t^{1.107}$	Chen and Mayne [13]	0.78	0.22
$OCR = (Q_t/3)^{1.2}$	Karlsrud et al. [14] ($S_t > 15$)	0.63	0.24
$OCR = (Q_t/2)^{1.1}$	Karlsrud et al. [14] ($S_t < 15$)	0.44	0.22
$OCR = 0.314Q_u^{1.35}$	Mayne and Holtz [12]	0.86	0.26
$OCR = 0.545Q_e^{0.969}$	Chen and Mayne [13]	0.88	0.34
$OCR = 1.026B_q^{-1.077}$	Chen and Mayne [13]	0.90	0.25
$OCR = 0.63B_q^{-1.286}$	Schroeder et al. [23]	1.31	0.28

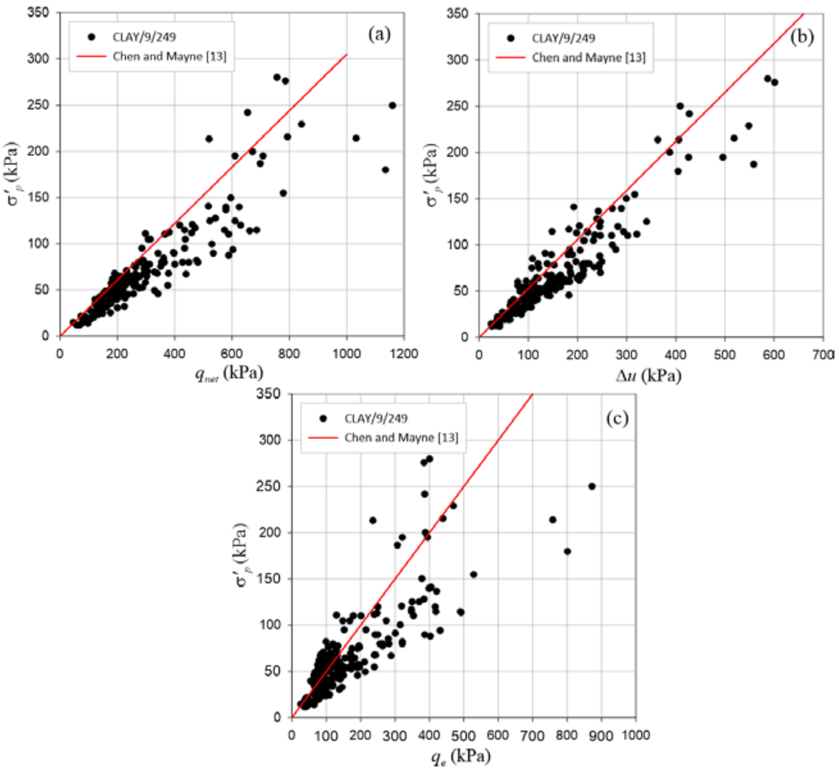

Figure 2. Comparison of CLAY/9/249 database with existing correlations for σ'_p.

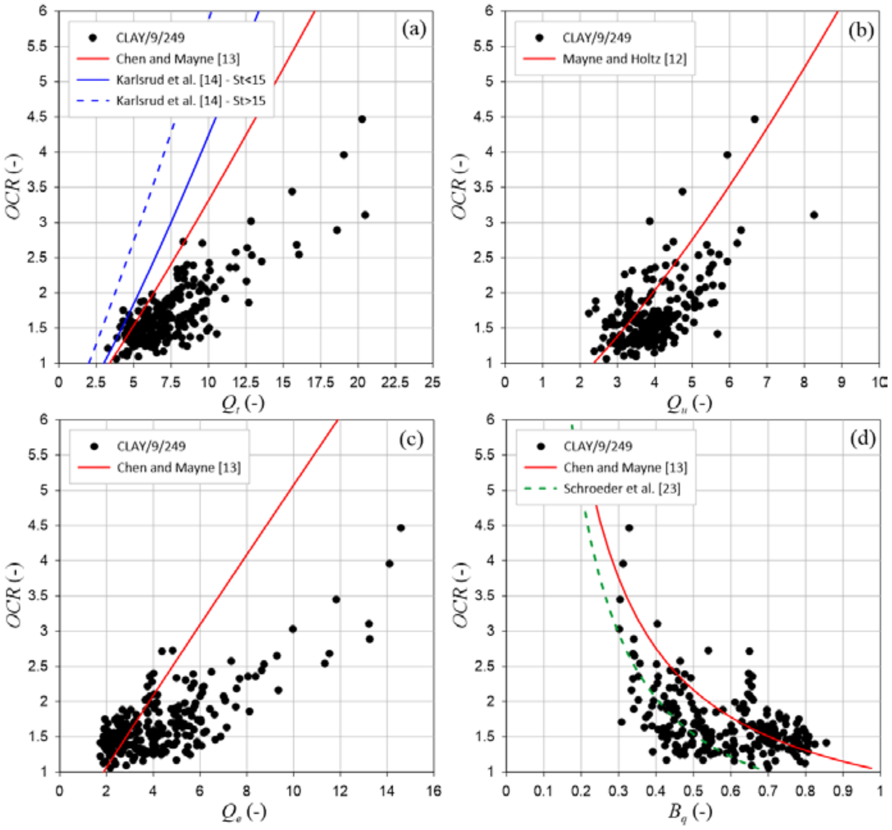

Figure 3. Comparison of CLAY/9/249 database with existing correlations for *OCR*.

4. CPTU-based correlations for σ'_p and *OCR* from CLAY/9/249 database

The compiled CLAY/9/249 database is used to derive improved CPTU-based correlations for σ'_p and *OCR* by means of linear regression analyses. Besides simple linear regression, multivariable regression is considered in order to maximize the coefficient of determination r^2.

The linear dependence between σ'_p, *OCR* and CPTU and index parameters is studied through the Pearson's correlation coefficient. The Pearson's correlation coefficient is a measure of the linear dependence (or correlation) between two variables. It has a value between +1 and −1, where 1 suggests total positive linear correlation, 0 no linear correlation, and −1 total negative linear correlation. As shown in Table 5, the strongest linear correlations are between σ'_p and q_{net}, σ'_p and Δu and *OCR* and Q_t. A weak linear correlation seems to exist between σ'_p, *OCR* and index parameters. This confirms the findings of Yang et al. [19].

Table 5. Pearson's correlation coefficient for different pairs of variables.

Parameter	q_{net}	Δu	q_e	Q_t	Q_u	Q_e	B_q	I_p	w	S_t
σ'_p	0.91	0.94	0.82	-	-	-	-	−0.15	−0.42	−0.10
OCR	-	-	-	0.81	0.59	0.76	−0.48	0.09	−0.17	−0.04

Table 6 presents the best-fit correlations from linear regression analyses. Following the indications of Table 5, the highest r^2 values in Table 6 are found between σ'_p and a combination of q_{net} and Δu. In general, correlations to σ'_p are characterized by higher r^2 compared to correlations to *OCR*. This is consistent with the observations made by Chen and Mayne [13]. The highest r^2 (= 0.93) was found for Eq 2 from a multivariable linear regression analysis between σ'_p and two variables, q_{net} and Δu. By adding further variables to Eq 2, the calculated r^2 does not increase significantly. Figure 4 shows a comparison between the measured and calculated σ'_p values from Eq 2. The majority of the data is within the ±20% boundaries.

$$\sigma'_p/p_a = 0.313(q_{net}/p_a)^{0.514}(\Delta u/p_a)^{0.511} \tag{2}$$

Table 6. Best-fit correlations for CLAY/9/249 database.

Correlation	Type	r^2
$\sigma'_p = 0.24q_{net}$	Linear	0.83
$\sigma'_p = 0.43\Delta u$	Linear	0.88
$\sigma'_p = 0.37q_e$	Linear	0.60
$OCR = 0.705+0.136Q_t$	Linear	0.66
$OCR = 0.385+0.327Q_u$	Linear	0.35
$OCR = 1.04+0.152Q_e$	Linear	0.57
$OCR = 1.261B_q^{-0.462}$	Power	0.26
$\sigma'_p/p_a = 0.313(q_{net}/p_a)^{0.514}(\Delta u/p_a)^{0.511}$	Power (multivariable)	0.93

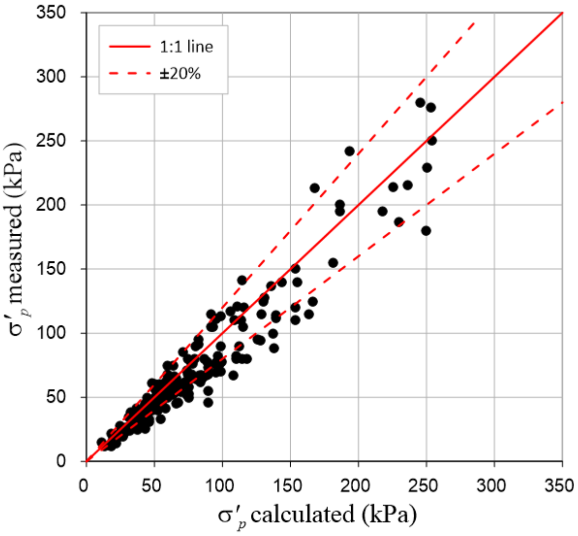

Figure 4. Comparison of measured vs calculated σ'_p from Eq 2.

5. Discussion

As discussed in the previous sections, several correlations exist in the literature for modeling stress history of clays from CPTU. This paper contributes to the geotechnical literature with new correlations and a high-quality database.

Sample quality clearly affects CPTU calibration and, therefore, correlations. The quality of the data used to derive correlations may vary significantly among the different literature sources. In these studies, sample quality is rarely discussed and, therefore, a possibility exists that the calibration data is not of high quality. In addition, even samples that are evaluated as “very good to excellent” according to Lunne et al.’s [5] criterion may not be of the highest quality. For instance, L'Heureux et al. [30] compared 72 mm piston and 250 mm block samples from Rakkestad sensitive clay in Southern Norway and observed how the block samples resulted in higher σ'_p and undrained shear strength, despite the comparable assessed sample quality. The data in the CLAY/9/249 database is considered to be of the best possible quality, especially in relation to the offshore data. That said, samples will still be characterized by a degree of disturbance that cannot be easily quantified.

One of the outcomes of the regression analyses (Table 6) is that the best relationship exists between σ'_p and a combination of q_{net} and Δu. In practice, the relationship between σ'_p and q_{net} is the one that is most commonly used, especially in offshore geotechnics. The relationship between OCR and Q_t is used in the same way, according to Eq 3.

$$k_1 = \frac{\sigma'_p}{q_{net}} = \frac{OCR}{Q_t} = k_4 = k \tag{3}$$

In absence of site-specific data, the coefficient $k = k_1 = k_4$ is often taken equal to 0.3, as suggested, for instance, by Chen and Mayne [13]. In this study, $k = 0.24$ was found. Indirectly, this study demonstrated that there is a weak correlation between k_j values and index properties. However, besides the site-dependency and the natural variability of soil properties, assuming a constant value of k_j may not always be a safe choice. Figure 5a plots k versus Q_t from the CLAY/9/249 database. The coefficient k shows a non-linear variation with Q_t, decreasing with increasing Q_t. For $Q_t > 10$, k

appears to become fairly constant. Similar behavior is observed with respect to Δu (k_2), q_e (k_3) and B_q (k_7), as shown in Figure 5b–5d. Despite the scatter, there is an indication that k_j = constant can be assumed when the normalized CPTU parameters (e.g., Q_t) vary within a reasonably small interval. This aspect becomes relevant especially in offshore clays that have been subjected to ice loading. In these cases, the normalized CPTU parameters may vary significantly with depth. Therefore, assuming k_j = constant may lead to a non-conservative solution.

The data in CLAY/9/249 covers *OCR* values ~1 to 5. The correlations and the recommendations given in this study should be then used carefully in presence of *OCR*s greater than 5. As discussed in Powell et al. [24], pore pressure measurements should not be used in heavily overconsolidated clays, where B_q can become very small or even negative.

Figure 5 further compares the CLAY/9/249 database with the large CLAY/10/7490 database compiled by Ching and Phoon [16]. Despite the high scatter, the large database shows similar trends as the CLAY/9/249 database.

Figure 6 illustrates Eq 3 for different values of *k*. The theoretical curves are compared with the data points in the CLAY/9/249 and CLAY/10/7490 databases. The lower and upper boundaries of k_1 can be identified at *k*~0.15 and *k*~0.40, respectively. Furthermore, *k*~0.15–0.5 seems to cover the majority of the data points in the CLAY/10/7490 database, which includes *OCR*s up to ~40. For onshore Norwegian clays, Paniagua et al. [31] found *k*~0.2–0.75 based on high-quality block sample data with *OCR* ~1–7. Based on the Authors' experience, data points for which *k* is less than 0.15 are likely to suffer of severe sample disturbance.

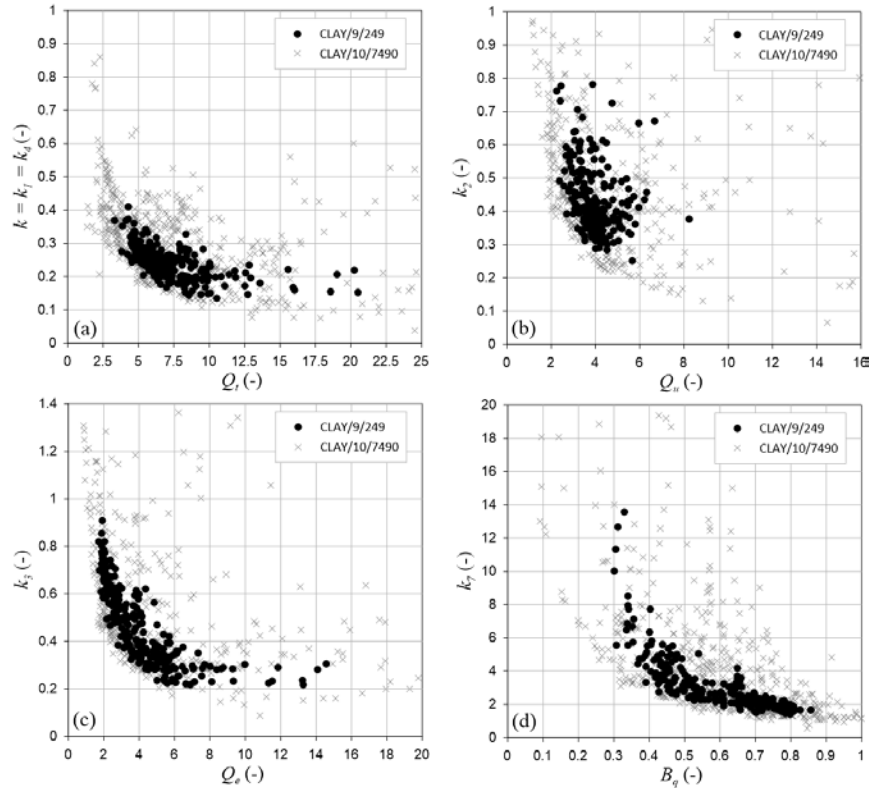

Figure 5. Variation of k ($= k_1 = k_4$), k_2, k_3 and k_7 with normalized CPTU parameters.

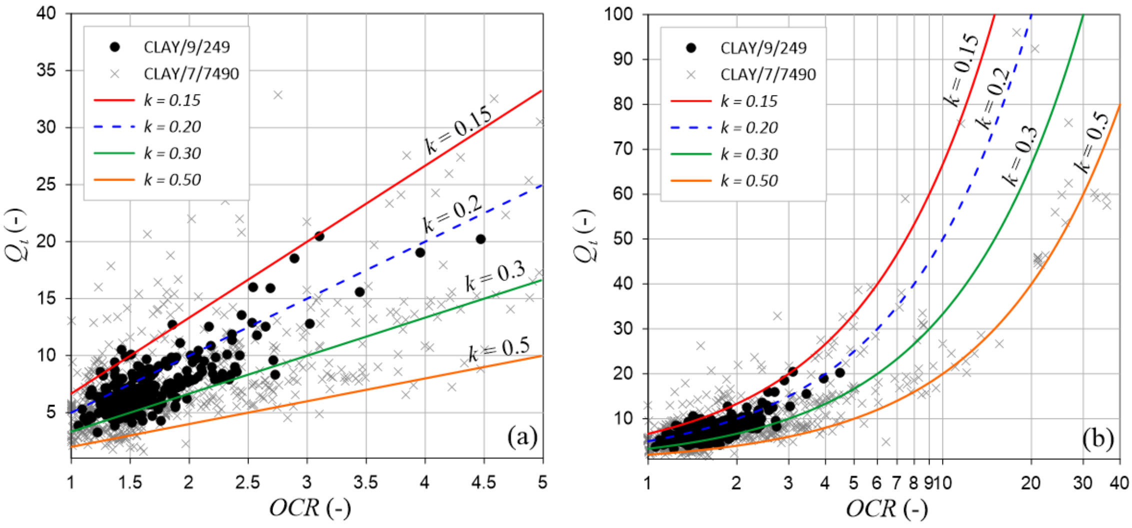

Figure 6. Q_t – *OCR* relationship and variability of the coefficient *k*.

6. Conclusions

This paper presents a multivariate database consisting of 249 high-quality onshore and offshore clay data points, labeled as CLAY/9/249 database. The database covers a wide range of basic clay parameters and *OCR* between 1 and 5. The new database is exploited to derive CPTU-based correlations for stress history of clays. Existing correlations are compared to the database and their uncertainties are quantified. The trends observed from the new data are confirmed by the existing large CLAY/10/7490 database [16]. In general, some of the new correlations in the present study have lower uncertainties than the majority of those proposed in the literature.

One of the main results of this study is that the relationship between σ'_p and a combination of q_{net} and Δu is characterized by a lower variability than the relationship between *OCR* and the normalized CPTU parameters. However, despite the high quality of the data points, correlations are still affected by uncertainties, which could not be justified by the variability in the index parameters. Therefore, the correlations proposed in this study should be used only for preliminary assessment of the in-situ stress history in the absence of site-specific data, or for comparison when the available data is limited or suspected to be unreliable.

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Conflict of interest

The authors declare no conflict of interest.

References

1. Bjerrum L (1973) Problems of Soil Mechanics and Construction on Soft Clays. State-of-the-art report. In *Proceedings, 8th ICSMFE*, Moscow 3: 111–159.
2. Ladd CC, Foott R (1974) A new design procedure for stability of soft clays. *J Geotech Geoenviron Eng* 100: 763–786.
3. Larsson R (1980) Undrained shear strength in stability calculation of embankments and foundations on soft clays. *Can Geotech J* 17: 591–602.
4. D'Ignazio M, Phoon KK, Tan SA, et al. (2016). Correlations for undrained shear strength of Finnish soft clays. *Can Geotech J* 53: 1628–1645.
5. Lunne T, Berre T, Strandvik S (1997) Sample disturbance effects in soft low plastic Norwegian clay. In *Proceedings of the Conference on Recent Developments in Soil and Pavement Mechanics, Rio de Janeiro*, 81–102.
6. Lunne T, Berre T, Andersen KH, et al. (2006) Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays. *Can Geotech J* 43: 726–750.
7. Di Buò B, Selänpää J, Lansivaara,T, et al. (2018) Evaluation of existing CPTu-based correlations for the deformation properties of Finnish soft clays. In *Cone Penetration Testing IV, Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT 2018), Delft*, 185–191.
8. Di Buò B, Selänpää J, Länsivaara T, et al. (2018) Evaluation of sample quality from different sampling methods in Finnish soft sensitive clays. *Can Geotech J.*
9. Paniagua P, L'Heureux JS, Yang SL, et al. (2016) Study on the practices for preconsolidation stress evaluation from oedometer tests. In *Proceedings of the 17th Nordic Geotechnical Meeting (NGM)*.
10. Robertson PK, Howie JA, Sully JP, et al. (1988) Discussion on Preconsolidation pressure from piezocone tests in marine clay by J.M. Konrad and K. Law. *Géotechnique* 38: 455–465.
11. Mayne PW (1986) CPT indexing of in situ *OCR* in clays. In *Proceedings of ASCE conference on Use of In-Situ Tests in Geotechnical Engineering (In-situ '86), Blacksburg*, 780–793.
12. Mayne PW, Holtz RD (1988) Profiling stress history from piezocone soundings. *Soils Found* 28: 16–28.
13. Chen BSY, Mayne PW (1996) Statistical relationships between piezocone measurements and stress history of clays. *Can Geotech J* 33: 488–498.
14. Karlsrud K, Lunne T, Kort DA, et al. (2005) CPTU correlations for clays. In *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering*, Balkema Publishers 16: 693.
15. Mayne PW (2017) Stress History of Soils from Cone Penetration Tests. *34th Manual Rocha Lecture, Soils and Rocks* 40: 203–218.
16. Ching J, Phoon KK (2014) Correlations among some clay parameters—the global database. *Can Geotech J* 51: 663–685.
17. Leroueil S (1996) Compressibility of clays: fundamental and practical aspects. *J Geotech Eng* 122: 534–543.
18. Lefebvre G, Poulin C (1979) A new method of sampling in sensitive clay. *Can Geotech J* 16: 226–233.

19. Yang SL, Lunne T, Andersen KH, et al. (2019) Undrained shear strength of marine clays based on CPTU and SHANSEP parameters. In *Proceedings of the XVII ECSMGE, Reykjavik, Iceland*. In Press.
20. Casagrande A (1936) The determination of the preconsolidation load and its practical significance. In *Proceeding of the First International Conference on Soil Mechanics and Foundation Engineering, Cambridge*, 60–64.
21. Janbu N (1963) Soil compressibility as determined by oedometer and triaxial tests. In *Proceeding of the European Conference on Soil Mechanics and Foundation Engineering* 1: 19–25.
22. Kolisoja P, Sahi K, Hartikainen J (1989) An automatic triaxial-oedometer device. In *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio De Janeiro*, 61–64.
23. Schroeder K, Andersen KH, Tjok K (2006) Laboratory testing and detailed geotechnical design of the Mad Dog Anchors. *Offshore Technology Conference*, 17949.
24. Powell JJM, Quarterman RST, Lunne T (1988) Interpretation and use of the piezocone test in UK clays. In *Penetration testing in the UK: Proceedings of the Geotechnology Conference organized by the Institution of Civil Engineers, Birmingham*, 151–156.
25. Leroueil S, Demers D, Martel LRP, et al. (1995) Practical use of the piezocone in Eastern Canada clays. In *Proceedings of the International Symposium on Cone Penetration Testing, CPT'95*, Sweden: Linköping, 2: 515–522.
26. Mesri G (2001) Undrained shear strength of soft clays from push cone penetration test. *Géotechnique* 51: 167–168.
27. Konrad JM, Law KT (1987) Preconsolidation pressure from piezocone tests in marine clays. *Géotechnique* 37: 177–190.
28. DeGroot DJ (2014) Evaluation of soft clay properties from interpretation of CPTU data within a SHANSEP framework. In *Proceedings of the 5th International Workshop: CPTU and DMT in Soft Clays and Organic Soils, Poland: Poznan,* 79–94.
29. Powell JJM, Lunne T (2005) Use of CPTU data in clays/fine grained soils. *Stud Geotech Mech* 27: 29–66.
30. L'Heureux JS, Gundersen AS, D'Ignazio M, et al. (2018) Impact of sample quality on CPTU correlations in clay–Example from the Rakkestad clay. In *Cone Penetration Testing IV: Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT 2018) Delft*, 395–400.
31. Paniagua P, D'Ignazio M, L'Heureux JS, et al. (2019) CPTU correlations for Norwegian clays: an update. *AIMS Geosci* 5: 82–103.

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