

CPTU correlations for clays

Corrélations CPTU pour les argiles

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ABSTRACT

New correlations between various CPTU factors, undrained shear strength and overconsolidation ratio have been developed for soft to medium stiff clays. The correlations are based on comparing the CPTU results against undrained triaxial compression strength and preconsolidation pressure determined on block samples of very high quality taken with the Sherbrooke 250 mm block sampler. The data base covers samples from 17 different sites ranging from soft to medium stiff clays with plasticity index from 10 to 50 % and sensitivity from 3 to about 200. The data clearly show that the measured excess pore pressure gives the best and most consistent correlation to the measured undrained strength. The cone resistance shows fairly large scatter, which may partly be an equipment/measurement problem and partly reflect that the cone resistance is a more complex parameter than the pore pressure response and which depends on more subtle clay characteristics. The cone factors also depend on the clay sensitivity and the plasticity index of the clays tested and the type of cone used.

RÉSUMÉ

De nouvelles corrélations entre les facteurs du piézocône CPTU et la résistance au cisaillement non-drainée et le rapport de surconsolidation sont proposées pour les argiles molles à moyennement raides. Ces corrélations ont été obtenues en comparant les résultats CPTU avec la résistance au cisaillement non-drainée en compression triaxiale et la pression de surconsolidation mesurées sur des blocs de haute qualité obtenus avec l'échantillonneur bloc 250 mm de l'Université de Sherbrooke. La base de données compte 17 différents sites d'argile, avec indice de plasticité entre 10 et 50 % et sensibilité entre 3 et 200. Les résultats montrent clairement que la pression interstitielle mesurée par le CPTU présente la corrélation la plus consistante avec la résistance au cisaillement non-drainée. La résistance en pointe du cône apparaît plutôt variable, en partie dû à l'équipement et la mesure elle-même, en partie dû au fait que la résistance en pointe est un paramètre plus complexe que la réponse des pressions interstitielles, et dépend de caractéristiques plus subtiles de l'argile. Les facteurs du piézocône dépendent aussi de la sensibilité et plasticité de l'argile.

1 INTRODUCTION

The cone penetrometer with measurement of pore pressure, called CPTU test, was developed in the late 1970's. The first publication on the CPTU was by Roy et al (1980). The CPTU test was initially a research tool which gradually came into commercial use, and first in connection with site investigations for offshore structures in the early 1980's. In Norwegian on-shore commercial practice it took until around 1990 before it found its place. It has by now (2004) gradually become the most common in-situ testing tool for determination of undrained strength of clay deposits in Norwegian site investigations, and has to a large extent replaced in-situ vane borings. This is mainly a result of the introduction of the wireless cone penetrometers manufactured by the Swedish companies ENVI (stores data in memory in the cone) and Geotech (transmits signals acoustically), which have greatly enhanced the efficiency of operations. In this context it may be mentioned that in Norway the CPTU-tests are almost exclusively carried out with one-manned advanced multi-purpose rigs. The production rate typically lies in the range 80-100 m pr. day.

The results of CPTU tests can in principal be used to derive a number of soil parameters related to stress history, shear strength and moduli values. Dissipation tests can also be used to assess the coefficient of consolidation and permeability. The derivation of such parameters in clays is generally based on semi-empirical correlations against parameters established through conventional soil sampling and laboratory tests. This paper deals only with CPTU tests in relatively soft to medium stiff clay deposits and the derivation of undrained shear strength and pre-consolidation stress based on comparisons against parameters determined exclusively by laboratory tests on very high quality block samples.

2 PROPERTIES OF CLAYS TESTED

In order to enable development of reliable correlations between CPTU-results and real in-situ soil parameters it is vital that such parameters are obtained by laboratory tests on high quality undisturbed soil specimens. Experience shows that it can be difficult to obtain samples of sufficiently good and indisputable quality with conventional commercial piston sampling, or standard Shelby tube sampling. The sample quality normally reduces with decreasing plasticity index and increasing sample depth and clay sensitivity (Karlsrud, 1991; Lunne et al 1997a). The effect of sample disturbance on measured undrained strength, pre-consolidation stress and stress-strain relations depend on the clay type. For many years the Norwegian Geotechnical Institute (NGI) has used the change in volume a sample undergoes during re-consolidation to in-situ effective stresses as an indicator of sample disturbance (Andresen and Kolstad, 1979). Lunne et al (1997a) proposed a modified scale for sample quality equal to the change in void ratio normalised by the initial void ratio.

To obtain high quality samples for establishment of more reliable reference parameters for CPTU correlations, NGI has since 1983 made use of the special Canadian Sherbrooke block sampler, Lefebvre and Poulin (1979), at several sites in Norway, (Lacasse et al., 1985), also in parallel with CPTU testing at the same sites (Karlsrud et al., 1996). According to the classification proposed by Lunne et al (1997a), the samples tested and included in this correlation study can be classified as very good to excellent.

The undrained strength determined by triaxial compression tests on samples consolidated anisotropically to the present in-situ effective stresses, s_u^{CAUC} (hereafter for simplicity defined as s_{uc}), has been chosen as the main parameter for comparison

against the CPTU results, combined with the pre-consolidation stress, p_c' determined by oedometer tests. All triaxial samples were sheared at a rate of about 0.6% pr. hour. In contrast with what can be the case for disturbed samples, all triaxial compression tests on the block samples showed a pronounced peak at failure. The axial strain at failure tended to increase with OCR from typically 0.3 to 1.2% for OCR less than 2 to 0.3 to 3.0% for OCR of 5. Figure 1 show an example of stress-strain curve for a block sample compared to piston samples.

The oedometer tests were in almost all cases constant rate of strain (CRS) tests, loaded at an axial strain rate of 0.5-1% pr.hour. For all samples tested the oedometer curves gave a very clear definition of the stress level at which the pre-consolidation stress, p_c' (or yield stress as defined by some, e.g. Burland, 1990), as illustrated by a typical example in Figure 2. The precise pre-consolidation stress was generally defined as an average from the Casagrande (1936) method and the Becker et al (1987) method, but these methods gave nearly identical results. It may be noted that the pre-consolidation pressure depends on the rate of straining, similar to the undrained strength. Thus the CRS tests used in this study normally give 5 to 20 % larger pre-consolidation pressures than conventional 24 hour incremental oedometer tests (Leroueil et al., 1983; Lunne, 2002).

The combination of CPTU-testing and block sampling has so far been carried out by NGI at 16 different locations in Norway. Table 1 presents typical range of index properties at the different locations. NGI has also been involved with block sampling and laboratory testing at the Bothkennar test site in the UK, which has also been included in this study. At each location block samples were taken from 2 to 5 different levels, giving a total of 58 tests to compare against CPTU results at the same locations and levels.

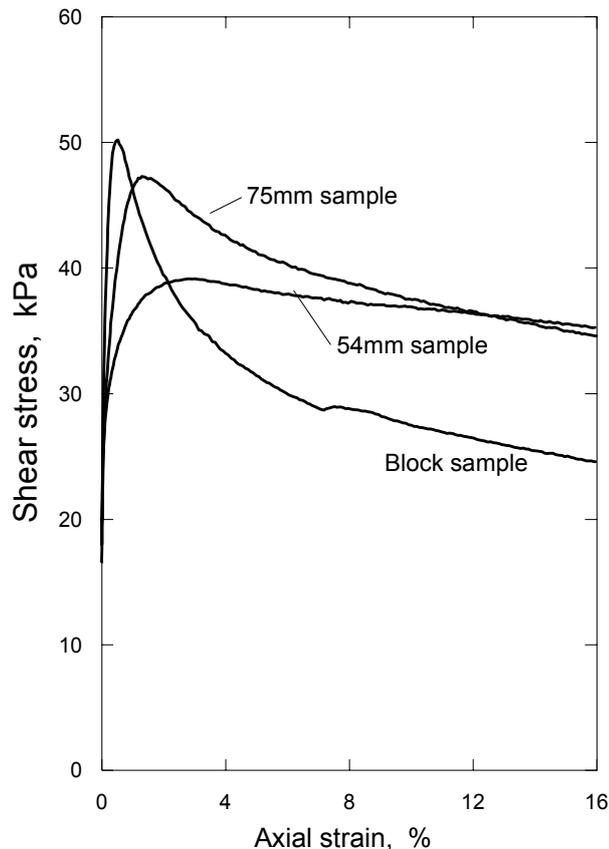


Figure 1. Example of CAUC triaxial test result on block sample compared to piston samples. Lierstranda $z=12.3$ m (from lunne et al 2002)

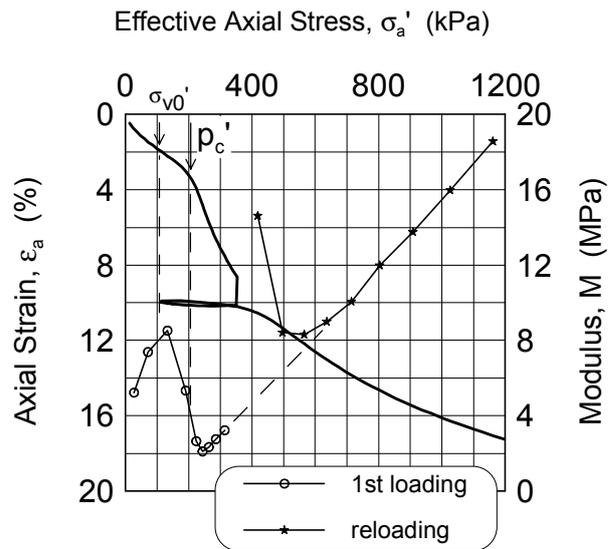


Figure 2. Example of oedometer test result. Lierstranda, $z=12.3$ m

Table 1: Index properties of clays tested

Location	Depth interval, m	Water content, %	I_p , %	Particles < 2 μm	S_t
Leira	7.2-15.9	30-34	12-14	36-49	7-10
Hvalsdalen 1	7.2-15.2	31-39	9-17	44-49	5-240
Hvalsdalen 2	7.2-12.4	36-38	12	40-46	15-20
Eidsvoll 1	5.7-14.7	25-33	13-19	37-48	2-5
Eidsvoll 2	10.4-13	25-26	13-14	38-42	2-4
Lierstranda	6.1-22.4	33-40	14-20	36-44	8-12
Bothkennar, UK	6.0-8.3	69-72	42-53	17-35	8-13
Emmerstad	4.1-5.9	37-44	7-11	40	77
Onsøy 1	3.1-9.1	59-72	28-44	21-35	7-12
Glava	5.6-6	33	17-18	29-34	7-10
Daneviks gt.	7.9-16.6	36-53	18-29	36-41	4-8
Nykirke	6.0-10.1	25-37	4-9	27-35	100-180
Kvenild	7.1-8.5	31-37	10-14	31-47	22-63
Onsøy 2	7.2-14.7	63-64	36-42	49-65	---
Buvika 1	7.1-15.1	29-31	6-7	29-30	55-160
Buvika 2	7.6-17.1	31-33	8-13	28-33	10-105
Kløfta-Nybakk	6.1-18.2	32-39	8-18	33-46	7-135

It should be noted that the sensitivities in Table 1 were determined from fall cone tests. The very high sensitivity of some samples is due to leaching of the original marine clay deposits. The sensitivity varies considerably with depth at some locations. Note also 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.

The mostly Norwegian marine clays tested were deposited in the sea after the last glaciation period about 10,000 years ago. The clay mineral content of these Norwegian clays is dominated by Chlorite and Illite/Muskovite (e.g. Kenney, 1967), and they have a low organic content (less than 2%). At the Bothkennar site in the UK the clay was deposited in estuarine conditions, Hight et al. (2003), and the clay has a different mineralogy compared to the Norwegian clays.

The clays tested showed undrained strength, s_{uc} , ranging from 15 to 150 kPa, and overconsolidation ratio, OCR, ranging from 1.2 to 6.3. The highest OCR-values were due to removal of overburden, otherwise it is generally due to secondary creep and/or chemical weathering.

Figure 3 presents the undrained triaxial compression strength determined on the various block samples in relation to the pre-consolidation stress in a normalised form of s_{uc}/σ_{v0}' versus overconsolidation ratio $OCR = p_c'/\sigma_{v0}'$, where σ_{v0}' is the in-situ vertical effective overburden stress. The measured data in Figure 3 are also compared to a range of correlation functions based on the SHANSHEP concept (Ladd et al, 1977), and defined by the equation:

$$s_{uc}/\sigma_{v0}' = \alpha \cdot OCR^m \quad (1)$$

where $\alpha = s_{uc}/\sigma_{v0}'$ for $OCR=1.0$, corresponding to a young truly normally consolidated clay which has not had the opportunity to develop any apparent pre-consolidation pressures due to secondary consolidation (e.g. Bjerrum, 1972).

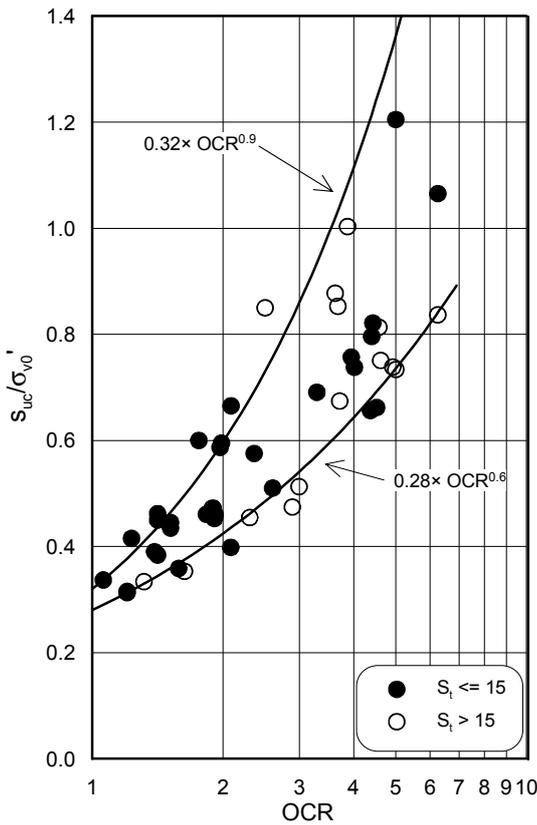


Figure 3. Normalized CAUC strength values, s_{uc}/σ_{v0}' , for block samples in relation to OCR

From Figure 3 it is apparent that these natural clays do not show such a unique relationship between undrained strength and OCR as has been indicated by testing clays that have been pre-consolidated artificially in the laboratory (e.g Ladd et al 1977). The reason may be that soil structure and possible local chemical bonding or cementation effects plays a role in-situ, which is lost when a sample is artificially pre-consolidated in the laboratory.

On many of the block samples the undrained strength has also been determined by triaxial extension tests (CAUE), s_{ue} , and direct simple shear tests (DSS), s_{uDSS} . Figure 4 compares these strengths to the triaxial compression strength. The data suggest somewhat larger anisotropy for the clays with high sensitivity (here taken as $S_t > 15$), and that the anisotropy decreases with increasing plasticity index, I_p . No clear dependence of the anisotropy on the overconsolidation ratio has been observed.

3 CPTU RESULTS AND CORRELATIONS

3.1 Definitions and CPTU factors considered

In the years passed since the CPTU test was first introduced, different cone factors have been used to relate the measured values of cone resistance and excess pore pressure generated during penetration of the probe to the undrained strength of clay deposits, e.g Lunne et al. (1997b).

In terms of measured pore pressures in CPTU tests the undrained strength is generally correlated to the pore pressure factor

$$N_{\Delta u} = \frac{u_2 - u_0}{s_u} \quad (2)$$

where u_2 = measured pore pressure at the location just behind the neck of the cone and u_0 = in-situ pore pressure. If a cone with pore pressure measurement in the tip is used, it may be possible to make a fair estimate of the u_2 pore pressure by application of a correction factor as given in Lunne et al. (1997b).

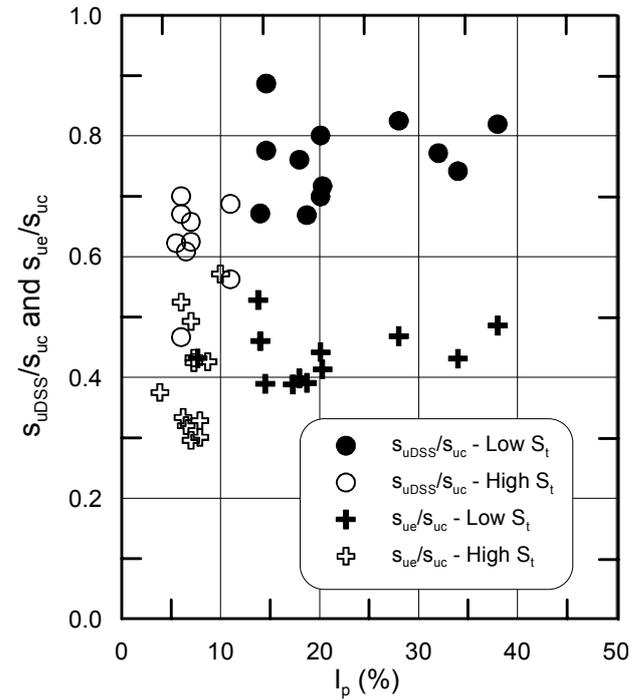


Figure 4. Measured anisotropic strength ratios s_{ue}/s_{uc} and s_{uDSS}/s_{uc} for the block samples

In relation to measured cone resistance it has become common practice to relate the undrained strength to the corrected cone resistance, q_t , rather than the directly measured tip resistance, q_c , through the normalised expression:

$$N_{kt} = \frac{q_t - \sigma_{v0}}{s_u} \quad (3)$$

where σ_{v0} = Total vertical overburden pressure

$$q_t = q_c + u_2(1-a)$$

and a = area ratio of the cone related to the area of the central part of the cone as compared to the gross area. The area ratio is determined by calibration tests in the laboratory as described in Lunne et al. (1997b). This area correction reduces or eliminates some of the observed difference in cone resistance obtained by using cones from different manufacturers.

In previous studies it has also been attempted to relate the undrained strength to a combination of the measured tip resistance and pore pressure through the expression

$$N_{ke} = \frac{q_t - u_2}{s_u} \quad (4)$$

In some previous studies (Lunne et al., 1985; Karlsrud et al., 1996) correlation plots between the corrected tip resistance factor N_{kt} on one axis against the pore pressure factor B_q on the other axis have been shown. B_q is defined as:

$$B_q = \frac{(u_2 - u_0)}{(q_t - \sigma_{v0})} \quad (5)$$

B_q is also equal to $N_{\Delta u} / N_{kt}$. A plot of N_{kt} against $B_q = N_{\Delta u} / N_{kt}$ is therefore misleading in the sense that it does not reflect the cone resistance factor N_{kt} at all because N_{kt} appears as a parameter on both axis. Such a plot actually only reflects how measured excess pore pressure vary with undrained strength. Correlation plots of N_{kt} and B_q are therefore, not included in this paper.

In previous studies (Lunne et al., 1989 and 1997b; Mayne, 1991) the overconsolidation ratio, OCR, has been tried correlated to the pore pressure parameters B_q , and $(u_2 - u_0) / u_0$ and the parameter Q_t defined as:

$$Q_t = \frac{(q_t - \sigma_{v0})}{\sigma'_{v0}} \quad (6)$$

These OCR correlations are also used and discussed later in this paper.

At the majority of the locations in this study the CPTU tests were carried out with the wireless ENVI 5^t cone which has an area ratio of $a = 0.69$ (Elmgren, 1995).

3.2 Note on reliability of measured CPTU parameters

It is very important that the CPTU data are as reliable as possible. The best way to achieve this is to carry out the tests following the requirements and guidelines given in the International Reference Test Procedure (IRTP) published by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, 1999).

Most equipment used for commercial soil investigations follow the above guidelines, but it is particularly important that the schemes for calibration of sensors and the procedures for recording zero readings before and after each test are adhered to. Reliable measurement of penetration pore pressures depends very much on good procedures for saturation of the pore pressure measurement system. Test results should be examined shortly after testing to identify possible errors.

However, even if the CPTUs are carried out following the IRTP, experiences indicate that results can vary with the cone penetrometer made from one manufacturer to another, even with present (2004) modern equipment.

NGI(2002) recently carried out a test programme at the Onsøy2 soft clay test site to investigate the variability between different cone penetrometers produced by different manufacturers. The Onsøy2 site has been used by NGI for many years and is a very uniform site. Four to five cone penetrometer tests were done with each of the 9 different cone penetrometers tested. Table 2 presents typical examples of variability in measured cone resistance and pore pressure.

Table 2 Typical results of comparative CPTUs at Onsøy2 test site (Based on NGI, 2002)

Depth, m	Corrected cone resistance, q_t			Measured pore pressure, u_2		
	Overall average (kPa)	Range sensores (% 1)	Total range (% 2)	Overall average (kPa)	Range sensores (% 1)	Total range (% 2)
10	589	±15.6	±16.5	452	±6.9	±12.8
20	898	±14.3	±14.9	681	±7.0	±13.2

- 1) Range between average readings from 9 different cone penetrometers
- 2) Total range including variability of all individual readings from different cone penetrometers (45 different CPTU soundings).

The results in Table 2 illustrate that the total range in cone resistance, q_t , is larger than the range in pore pressure, u_2 , and also that the measured pore pressure is significantly less dependant on the type of cone penetrometer compared to the cone resistance. The reason why there is larger variation in cone resistance compared to the pore pressure is not fully understood, but it is a fact that the measured pore pressure is generally a much higher percentage of the capacity of the pore pressure sensor compared to the cone resistance and capacity of the load cell.

For some of the sites listed in Table 1 the CPTUs were carried out more than 20 years ago. Since considerable equipment improvement has taken place since then it is to be expected that the inherent uncertainties associated with the CPTU measurements may be larger than illustrated in Table 2. This also applies to the ENVI cone used in most of this study.

3.3 Undrained strength correlations

The data from this study clearly show that the pore pressure response gives the most consistent and best correlations to the undrained s_{uc} strength determined on the block samples. Figure 5 shows the derived values of $N_{\Delta u}$ versus measured overconsolidation ratio, OCR, on the block samples. These data have been grouped into two ranges of sensitivity of S_t smaller or larger than 15, which has a systematic impact on the excess pore pressure and $N_{\Delta u}$. This is seen more clearly in figure 6 which shows $N_{\Delta u}$ directly against sensitivity for different ranges of OCR. Figure 7 shows that $N_{\Delta u}$ also to some extent depend on the plasticity index, I_p . As discussed in Section 2 of this paper I_p is a parameter that can be misleading for clays with high sensitivity. Figure 7 also suggest that the plasticity index is a secondary parameter for the sensitive clays. On basis of a detailed study of the combined impact of OCR, S_t and I_p on the results, it is proposed typical average correlations accounting for their combined effects as follows:

For low sensitive clays ($S_t < 15$)
 $N_{\Delta u} = 6.9 - 4.0 \log OCR + 0.07(I_p)$ I_p in % (7a)

For high sensitive clays ($S_t > 15$)
 $N_{\Delta u} = 9.8 - 4.5 \log OCR$ (7b)

These correlations are illustrated in fig.5 for an average I_p -value of 22.4% for low-sensitive clays. Typical curves based on eq's 7a) and 7b) are also shown in Figs. 6 and 7 for ranges of OCR values, and using an overall average $I_p = 22.4$ for $S_t < 15$. The exact average OCR value corresponding to the different ranges in the data base are as follows:

Range OCR	Average OCR
1-2	1.57
2-4	2.92
>4	4.90

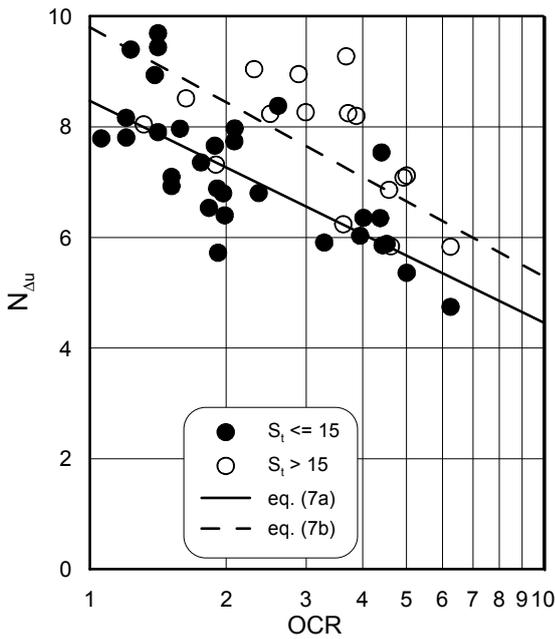


Figure 5. Relationship between $N_{\Delta u}$ and OCR

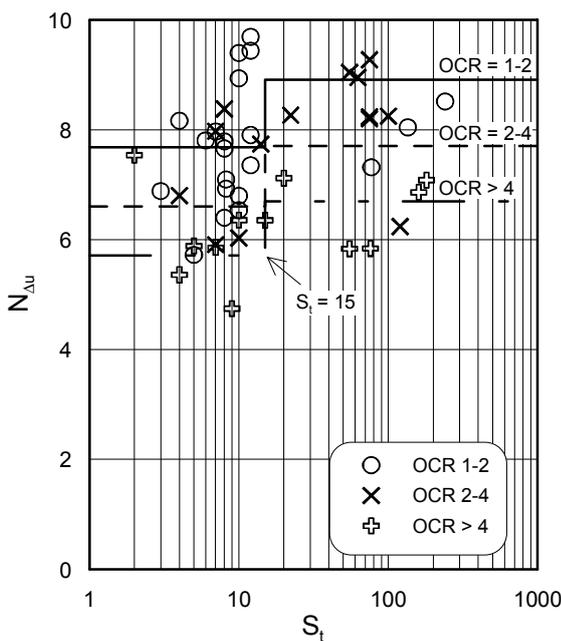


Figure 6. Influence of sensitivity on $N_{\Delta u}$

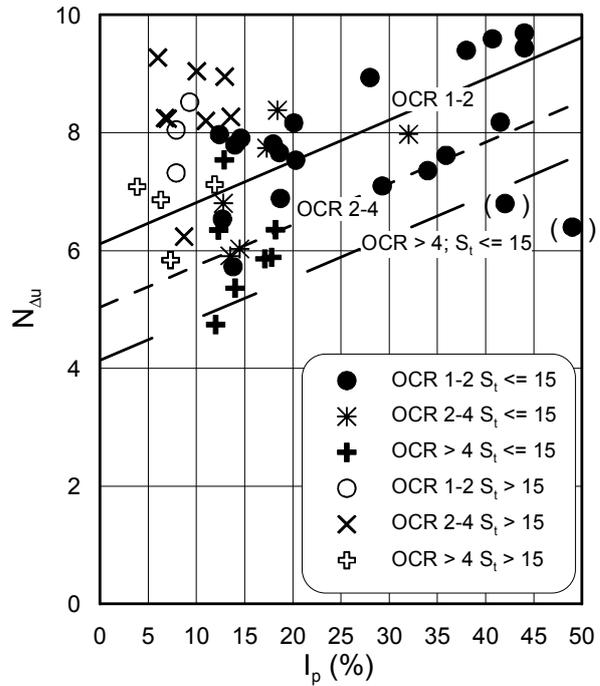


Figure 7. Influence of plasticity index on $N_{\Delta u}$

Assessment of scatter in the data suggests that there is a variation in strength of about $\pm 10-15\%$ when the correlations above are applied. Some of this variation is believed to be equipment and procedure related, and can depend on the cone penetrometer used and workmanship as discussed in section 3.2 above. Some of the scatter in the correlations may also be due to changes in design and improved accuracy of the cones used over this 20 year time period.

A special comment is made to the two points put in bracket in Fig.7. These represent the Bothkennar UK site. Hight et al. (2003) have suggested that the plasticity index as measured by standard test procedures could be much too high, because it has high organic content. These points were therefore given no weight when the effect of I_p was assessed. Finally, it is also quite possible that other and more subtle soil parameters in reality influence the results and contributes to some of the scatter. This could for instance be the detailed stress-strain relation for the clay, including the large strain post-peak behaviour, and the anisotropic nature of the undrained shear strength. Even for the block samples there may also be some scatter due to disturbance effects, but this is believed to be less than $\pm 5\%$.

It is a bit unfortunate that the cone factor $N_{\Delta u}$ depends of the overconsolidation ratio, which requires good sample quality to determine precisely. The dependency is however, not so strong. A fair estimate of OCR based on geologic history can be made in some cases. An alternative is to first tentatively estimate OCR, then use the first estimated $N_{\Delta u}$ and calculated s_{uc} value to estimate a new OCR on basis of Figure 3, and use that OCR as new basis for assessing a revised $N_{\Delta u}$ and undrained shear strength. One or two iterations may be needed to define the final value. The first estimate of OCR can also be made on basis of the CPTU correlations described later in the paper.

Figures 8, 9 and 10 show similar relationships between the cone factor N_{kt} , OCR, S_t and I_p . It is readily observed that these relationships show far more scatter than the $N_{\Delta u}$ relationships in Figs. 5 to 7. This could either be due to less accuracy of the sensors measuring cone resistance, or that the cone resistance even more than the pore pressure depends on other and more subtle soil parameters than OCR, S_t and I_p . Tentative best fit correlations are as follows:

For low sensitive clays ($S_t < 15$)
 $N_{kt} = 7.8 + 2.5 \log OCR + 0.082 I_p$ (8a)

For high sensitive clays ($S_t > 15$)
 $N_{kt} = 8.5 + 2.5 \log OCR$ (8b)

Figures 8-10 also show typical correlation functions according to eq's 8a) and 8b). The variation in calculated undrained strength based on these correlations typically lie around $\pm 15\%$ for the high sensitive clays and $\pm 30\%$ for the low sensitive clays.

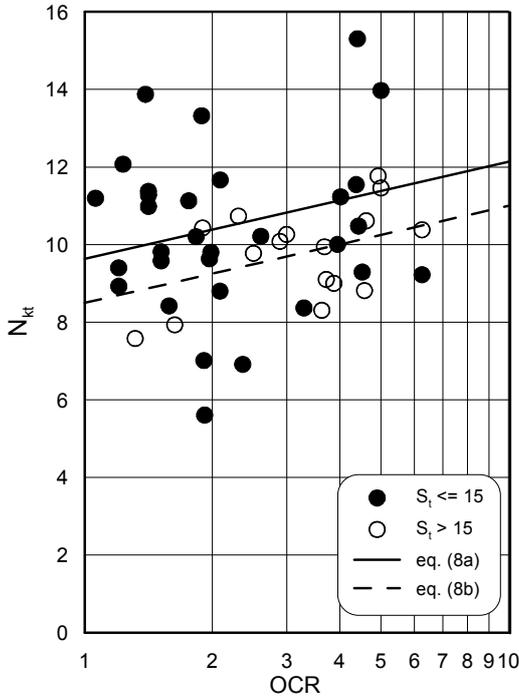


Figure 8. Relationship between N_{kt} and OCR

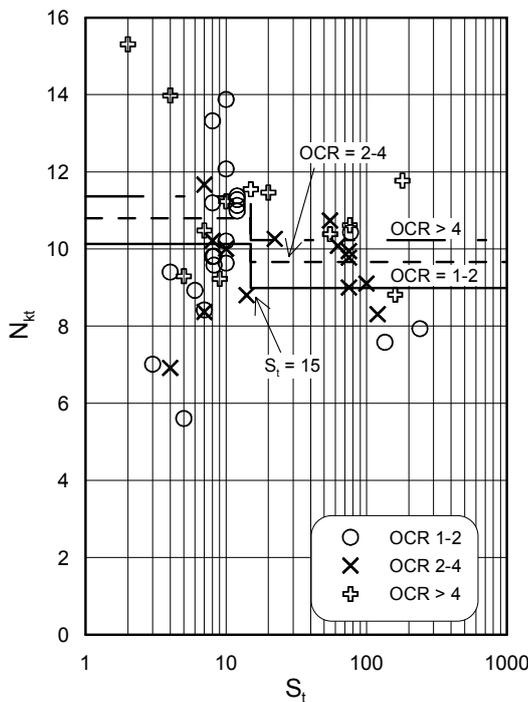


Figure 9. Influence of sensitivity on N_{kt}

Figure 11 compares shear strengths calculated from a series of 35 different CPTU-tests carried out in the Oslo harbour basin in a clay deposit that in geologic terms should be essentially normally consolidated. The CPTU tests cover an area of about 100 by 250 m. The water depth is typically 8-10 m, and the clay is rather homogenous with a water content in the range 35-45 %, generally decreasing with depth. The strengths were computed on basis of equations 7a) and 8a) accounting for a decrease in plasticity index from about 25% in the top to 15 % in the bottom and taking $OCR=1.3$ and constant with depth. Figure 11 confirms the larger scatter in strength from N_{kt} than from $N_{\Delta u}$ that was also suggested by Table 2, with a variation of typically $\pm 20\%$ and $\pm 10\%$ respectively. It may however, be noted that the absolute variation is close to constant with depth. Another interesting observation that can be made from figure 11 is that the undrained shear strengths, s_{uc} , based on $N_{\Delta u}$ increase essentially linearly with depth, as was expected for this normally consolidated deposit. The s_{uc} values based on N_{kt} does not show the same linear trend and is higher than based $N_{\Delta u}$ in the top, but then fall off with depth relative to the $N_{\Delta u}$ strength profile. This suggests a depth influence on N_{kt} . Figure 12 compares the strength ratios directly. Herein is also included a depth correction factor I_z applied to the strength arrived at from N_{kt} to try to match the strength from $N_{\Delta u}$. I_z is defined by the expression:

$$(S_{uc})_{N_{kt}} = I_z (S_{uc})_{N_{\Delta u}} \quad (9)$$

$$I_z = (1 - a(z - z_{ref})/z)^b \quad \text{with } z_{ref} = 16\text{m}, a = 0.45, b = 0.75 \text{ as best fit}$$

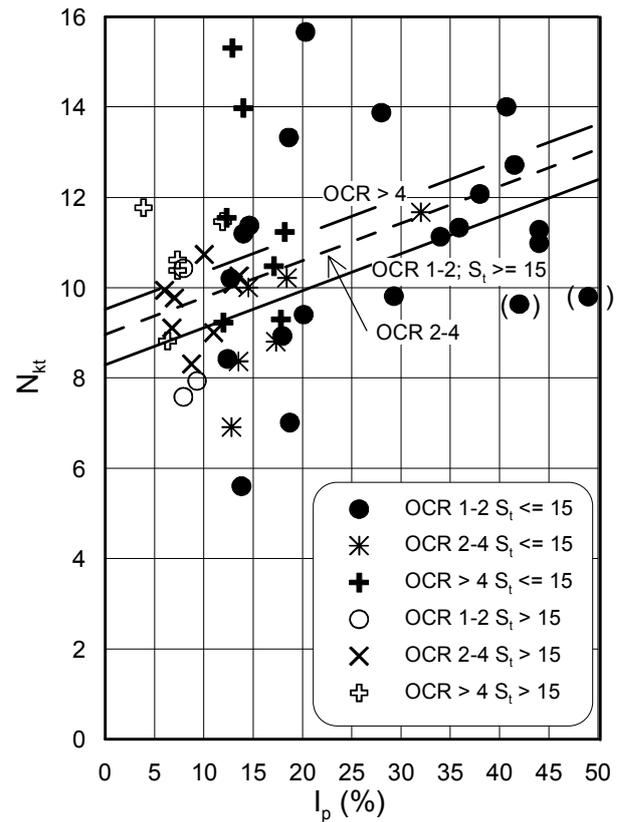


Figure 10. Influence of plasticity index on N_{kt}

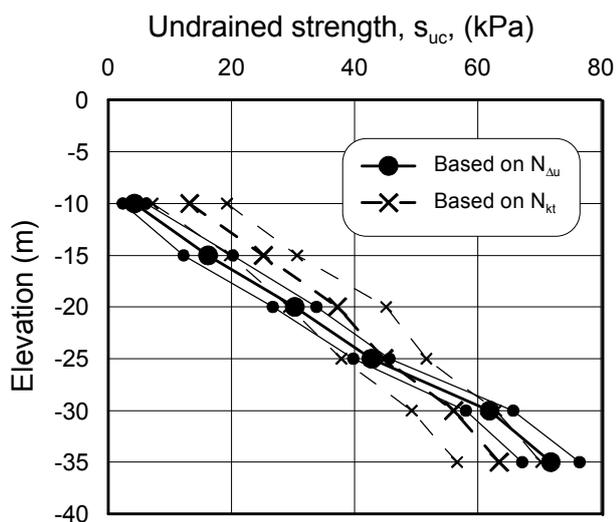


Figure 11. Comparison between strengths from cone resistance and pore pressure in Bjørnvika, Oslo harbour

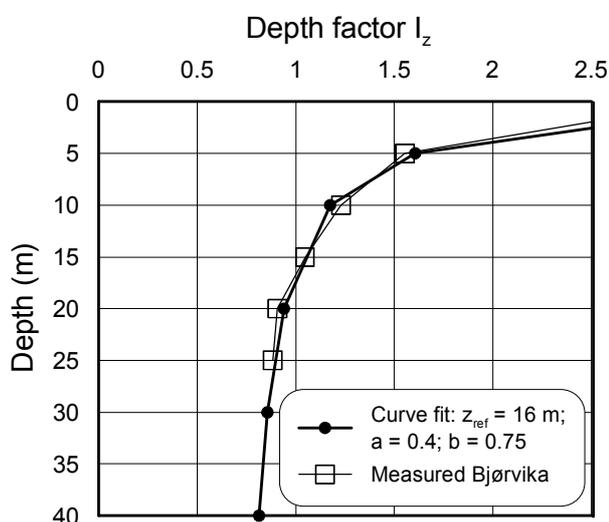


Figure 12. Depth factor on I_z suggested by data from Bjørnvika in

The block sampling data presented in this paper has not made it possible to sort out if this is a general depth effect, and if the expression (9) is representative for other clay profiles or other cone penetrometer types. Further comparative and statistical studies at different sites and with different cone penetrometers are needed to get a better grasp on this potential depth influence.

The cone factor N_{ke} contains both corrected cone resistance and excess pore pressure, equation (4). Figure 13 shows that this cone factor gives very large scatter when plotted against OCR. Figure 14 shows on the other hand that N_{ke} is better related to the pore pressure factor B_q . The advantage of this correlation is that it does not require any independent estimate of OCR. It has not been possible to identify any significant dependency of this correlation on plasticity index of the clay, but it depends somewhat on sensitivity. The typical average lines in Figure 14 are represented by the following equations:

$$\text{For low sensitive clays } (S_t < 15) \\ N_{ke} = 11.5 - 9.05B_q \text{ with } N_{ke} = 2.0 \text{ as a lower limit} \quad (10a)$$

$$\text{For high sensitive clays } (S_t > 15) \\ N_{ke} = 12.5 - 11.0B_q \text{ with } N_{ke} = 2.0 \text{ as a lower limit} \quad (10b)$$

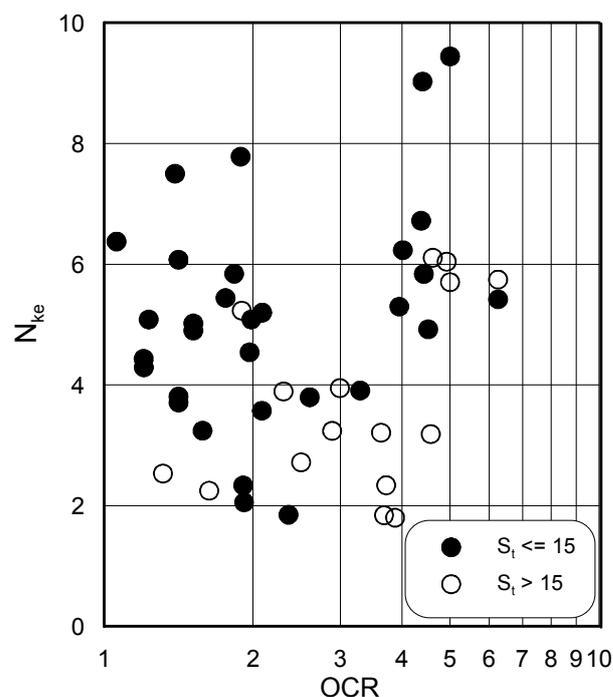


Figure 13. Relationship N_{ke} and OCR

These correlations should be used with caution for values of B_q less than about 0.6, as there is little data in that range, and the data also suggest a non-linear trend for low B_q values. It may also be noted that the variation in N_{ke} around the average line is about ± 1.0 at all levels of B_q . This means as an illustration, that the variation in strength increase from $\pm 15\%$ at $B_q = 0.6$ to $\pm 33\%$ at $B_q = 0.9$. This variation or uncertainty in calculated strength is larger than when using the pore pressure response alone, but is generally better than when using the cone resistance alone when B_q is less than about 0.7-0.8.

In engineering practice the authors recommend that all three cone factor correlations (based N_{Au} , N_{kt} , and N_{ke}) are used to determine the undrained strength, but that most weight is given to strengths arrived at from N_{Au} . A comparison between these strengths may also help to reveal apparent inconsistencies or problems with the individual CPTU tests. For instance will low s_{uc} values based on N_{Au} , compared to the other two often give an indication of poor saturation of the piezometer system.

It is also important to bear in mind that the undrained strength determined on high quality block samples can be considerably larger than on samples taken with conventional piston sampling, and that the block samples also show far more pronounced strain softening beyond peak than poorer quality samples. A designer must keep that in mind when using the strengths derived from the CPTU correlations proposed herein.

If the correlations are to be applied to distinctly different clays from the mostly Norwegian marine clays covered in this study, it is recommended to verify the applicability of the proposed correlations by similar block sampling and testing as described herein. The cone factors have also to some extent been found to depend on the cone penetrometer used (e.g. Table 2 and NGI,2002), which may also warrant some independent verification of the applicability of the correlations. Even for large and important projects in Norway it is the authors' recommendation to carry out block sampling and verify the applicability of the correlations for specific CPTU equipment used. Examples of combination of CPTU testing and block for actual projects were presented by Karlsrud (1999) and Jensen (2001). These examples showed that the undrained strengths as a result of such investigations could be upgraded by 20-30%, which led to very substantial cost savings for the projects in question.

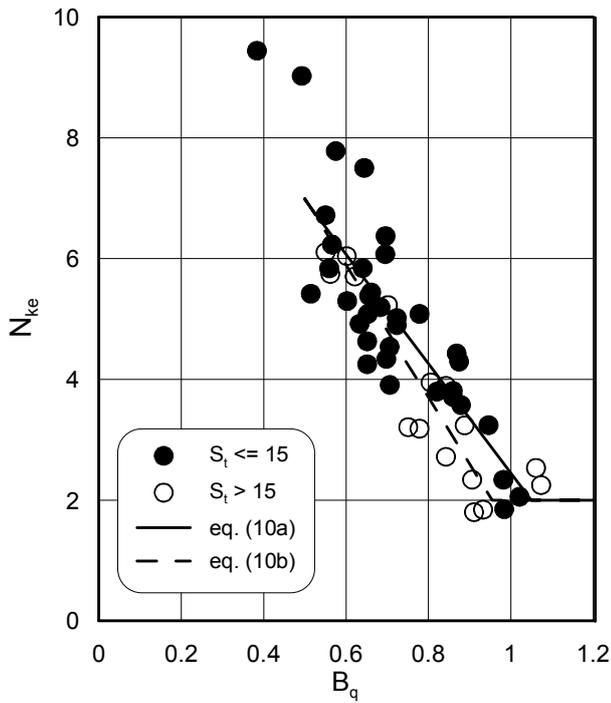


Figure 14. Relationship N_{ke} and B_q

3.4 Correlations for overconsolidation ratio, OCR

Figure 15 shows that there is a correlation between the cone factor B_q (eq. 5) and OCR, but the scatter is fairly large, which also agrees with data presented in Fig.5.14 of Lunne et al. (1997b). A similar and slightly better correlation was found between the normalised excess pore pressure $(u_2-u_0)/\sigma'_{v0}$ and OCR, Figure 16, but the best correlation was found between the cone factor Q_t (eq. (6)) and OCR, Figure 17. The typical average value of OCR according to Fig.17 corresponds to:

$$\text{OCR} = (Q_t/3)^{1.20} \quad (11a)$$

$$\text{OCR} = (Q_t/2)^{1.11} \quad (11b)$$

Even use of Figure 17 will give significant uncertainty in estimated OCR, and relatively speaking much larger than for the correlations between CPTU results and the undrained shear strength. One reason for that may be the inherent variability in the actual relation between in-situ undrained strength and OCR, as shown by Figure 3. As for the undrained shear strength it is recommended to use all correlations on specific projects.

4 CONCLUSIONS

The correlations presented herein between various cone resistance factors and the true in-situ undrained triaxial compression strength of samples consolidated anisotropically to in-situ effective stresses prior to shearing, s_{uc} , show that the pore pressure factor gives the most consistent correlations, and is recommended as the best factor for determination of s_{uc} . The cone factor $N_{\Delta t}$ depends however on the overconsolidation ratio, OCR, the sensitivity, S_t , and the plasticity index, I_p , of the clay. The reliability of the strength arrived at lie around $\pm 10\%$, provided of course that the CPTU equipment and procedures used deter-

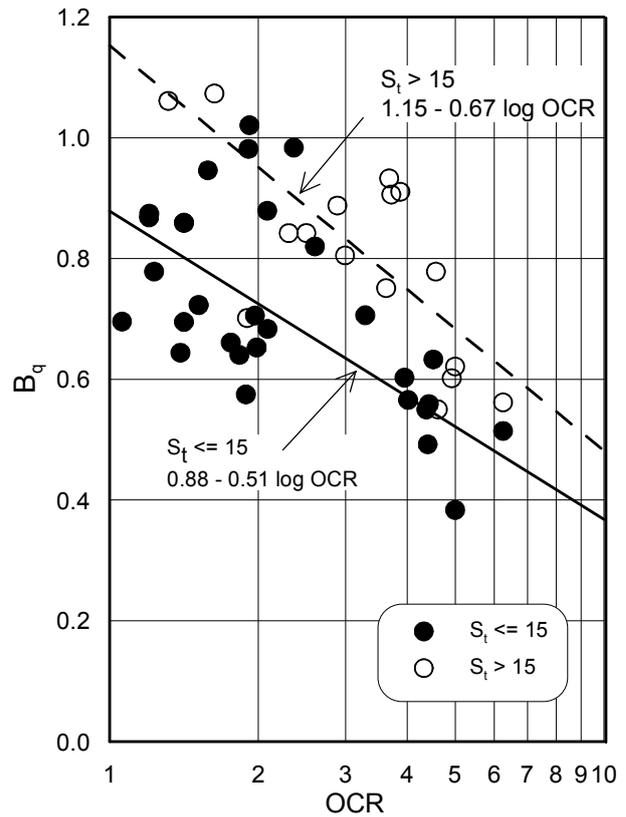


Figure 15. Relationship B_q and OCR

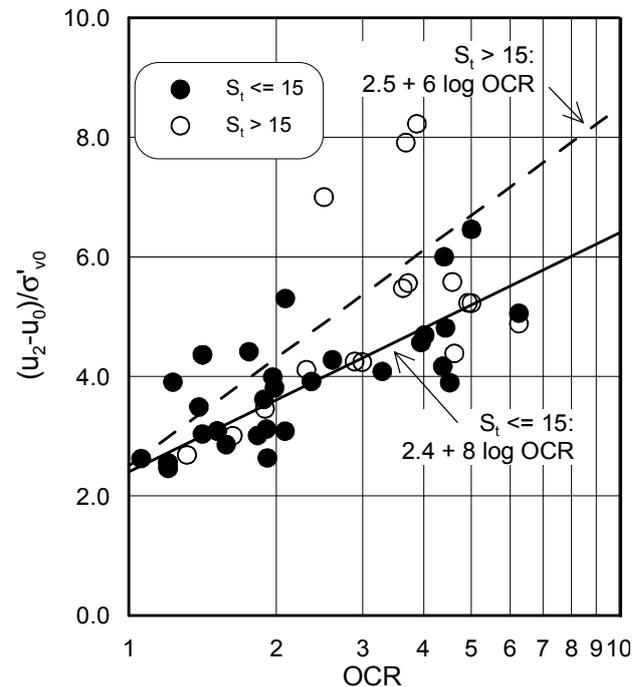


Figure 16. Relationship normalised excess pore pressure $(u_2-u_0)/\sigma'_{v0}$ and OCR

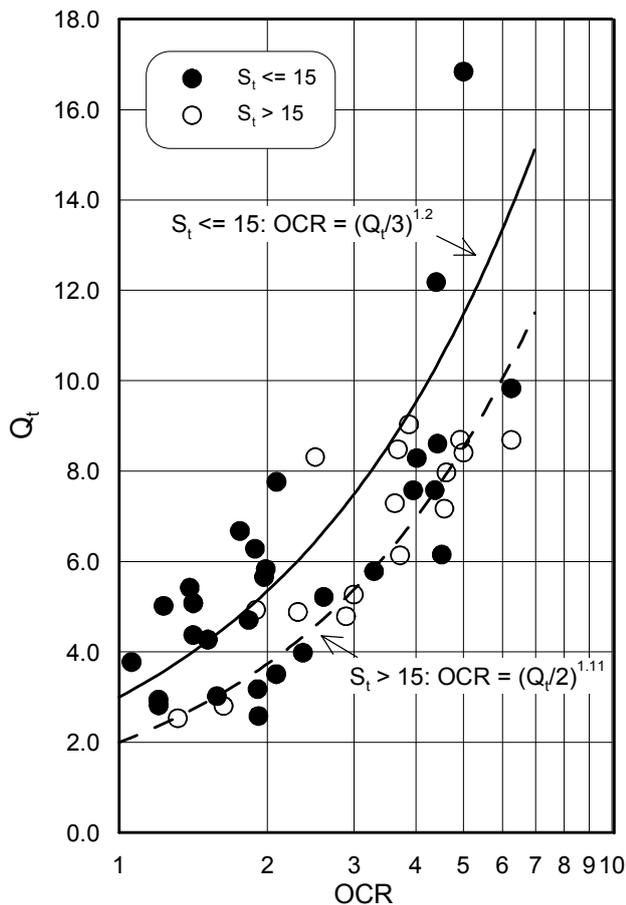


Figure 17. Relationship Q_t and OCR

mines the pore pressure in a reliable manner. For most cones on the market today, this should not be a problem, but it requires good follow up and checking of saturation procedures, zero readings and calibration factors.

The cone resistance factor N_{kt} , give in general poorer correlations against undrained strength than the pore pressure response. This may partly be an equipment problem but possibly also reflect that the cone resistance depends on more subtle soil parameters like for instance the stress-strain relation up to and beyond peak. The data from Oslo harbour (Figures 11 and 12) also indicate that there may be a depth influence on N_{kt} which should be investigated further.

The effective cone factor N_{ke} , combining both cone resistance and pore pressure response, lies somewhere in between the $N_{\Delta u}$ and N_{kt} factors when it comes to variability. However, for values of B_q larger than 0.7-0.8 the variability in N_{ke} becomes rather large. It is still recommended to use both the N_{ke} and the N_{kt} correlations to verify the undrained strengths arrived at from $N_{\Delta u}$.

When using the strengths derived from the proposed CPTU correlations, a designer must keep in mind that the undrained strength determined represent the peak undrained triaxial compression strength on high quality samples.

The data suggest that the best estimate of overconsolidation ratio can be made from the normalized cone resistance factor Q_t , but the correlation is not nearly as good as for predicting the undrained strength.

It should finally be noted that the correlations herein have been developed from a data base mainly containing results for Norwegian marine clays, and mainly using the cone penetrometer by ENVI. If applied to distinctly different clays and/or using different CPTU equipment it is encouraged to verify the applicability of the proposed correlations by similar comparisons be-

tween results of block sampling and CPTU results as described herein. Even for large and important projects in Norway it is the authors' recommendation to verify the applicability of the correlations in such a manner.

It can finally be mentioned that it is NGI's and the authors' intention to regularly update the database, also including data that in the future may become available through others.

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