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EXPERIENCE WITH CPTU, T-BAR AND BALL PENETROMETERS IN TWO SOFT CLAYS

T. LUNNE

Norwegian Geotechnical Institute, Oslo, Norway

Abstract: Field developments in deep waters with very soft soils have led to increased reliance on the use of in situ tests to evaluate soil design parameters. Recently the T-bar and ball penetrometers have been introduced due to their potential for increasing the reliability of interpreted undrained shear strength relative to the CPTU for soft clays. Empirical correlations based on field tests and laboratory tests on samples at two onshore soft clay sites indicate that T-bar correlation factors are in a somewhat narrower range compared to cone factors. Recommendations are given in terms of cone and T-bar factors to use.

1. INTRODUCTION

Since the introduction of the cone penetration test in offshore soil investigations in the North Sea in 1972, it has become standard practice to base soil parameters for foundation design on CPT/CPTU results and laboratory tests on obtained samples (e.g., LUNNE [5]).

With the trend to develop fields in gradually deeper water with very soft soils, there are problems with obtaining accurate CPTU data due to the large readings of the sensors on the sea bottom. The additional load on the sensors when penetrating soft soils are small compared to the initial readings on the seabed. There are also difficulties with obtaining high-quality undisturbed samples due to handling equipment in large water depth and also due to the large stress relief when samples are brought up to deck level. Especially if there is some gas dissolved in the pore water, the gas will come out of solution due to large stress relief, expand and damage the soil structure (LUNNE et al. [7]). Laboratory tests on soils that are disturbed in this way will result in measured soil parameters that are not representative of in situ conditions.

It is therefore a need to consider in situ tests that can give more reliable soil parameters. Recently the T-bar and ball penetrometers have been introduced to offshore soil investigations (RANDOLPH et al. [12], RANDOLPH [10]). Both the T-bar and the ball have a larger area, giving higher resolution in the measured penetration resistance. The other advantage of the T-bar and the ball is that they are the so-called full flow penetrometers, which means that for computation of the undrained shear strength the total vertical stress need not to be subtracted as for the CPTU cone resistance. This paper presents some results of a project carried out jointly by the Norwegian Geotechnical Institute (NGI) and The Centre for Offshore Foundation Systems (COFS). CPTU, T-bar and ball tests have been carried out at the onshore soft clay test sites in Onsøy in Norway (NGI) and Burswood in Australia (COFS). At both sites the results of the CPTUs and the T-bar tests have been used to compute cone and T-bar factors based on correlations between undrained shear strength measured by triaxial and direct simple shear tests carried out on high quality samples. Although the introduction of the T-bar and the ball has been the result of deep water developments, the two penetrometers can also be used onshore (e.g., LONG and GUDJONSSON [4]).

Most of the CPTU and T-bar results included in this paper have been taken from LUNNE et al. [9].

2. DESCRIPTION OF SITES AND REFERENCE SOIL PARAMETERS

Onsøy test site, Norway

This onshore soft clay site has been used by NGI for more than 30 years. It is described in detail by LUNNE et al. [8]. Figure 1 shows a soil profile close to the location where the CPTUs and T-bar and ball tests described in this paper have been carried out. The reference undrained shear strength parameters included in figure 1 have been obtained by CAU (anisotropically consolidated undrained triaxial) tests sheared in compression (CAUC) and in extension (CAUE) and DSS (direct simple shear tests) carried out on high quality samples taken with the Canadian Sherbrooke block sampler (LEFEBVRE and POULIN [3]).

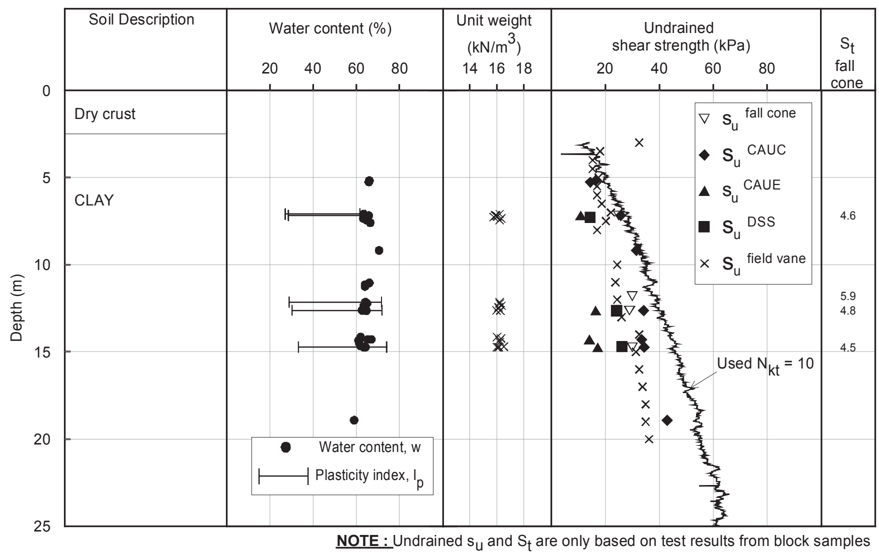

Fig. 1. Soil profile, Onsøy test site

Burswood test site, Australia

This onshore soft clay site is used by University of Western Australia and COFS for research purposes. Figure 2 shows a soil profile at the location where the present CPTUs and T-bar tests were carried out. The reference CAUC, CAUE and DSS tests shown in figure 2 have been carried out on tube samples (71–104 mm dia.). It should be borne in mind that the quality of these samples is not as good as those from the block sampler used at Onsøy.

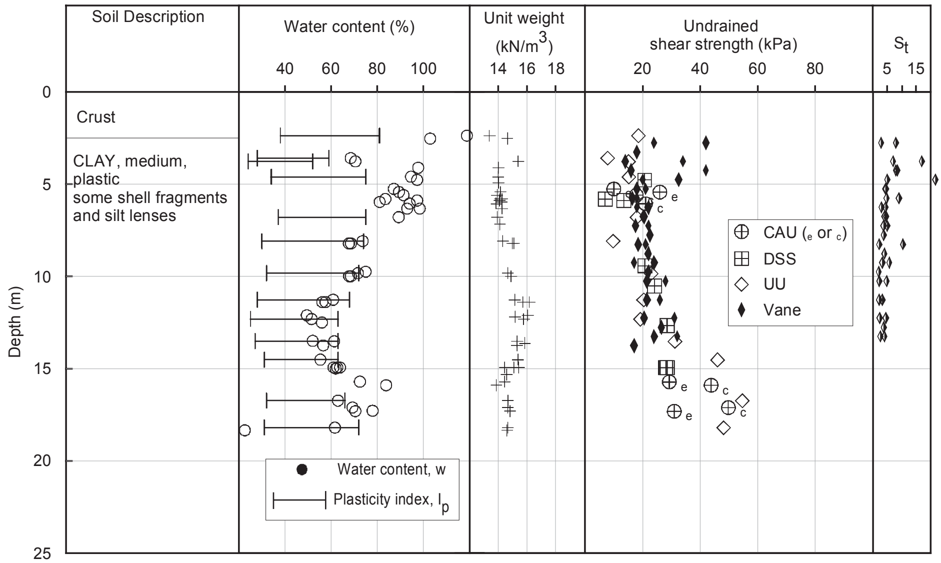

Fig. 2. Soil profile, Burswood tests site

3. EQUIPMENT AND PROCEDURES

The cone penetration tests have been carried out with equipment and procedures according to the International Reference Test Procedure (IRTP) published by the International Society of Soil Mechanics and Geomechanical Engineering (ISSMGE [2]). In particular the tests at NGI have been done with the ENVI memocone and the tests at Burswood with the Hogentagler cone penetrometer. Pore pressure has been measured at the location just behind the cone, the so-called u_2 position, for the Onsøy and Burswood tests. The measured cone resistance has been corrected for the effects of pore pressure as required in the IRTP. The results below are reported in terms of the measured sleeve friction f_s, the corrected cone resistance q_t and the measured pore pressure u_2.

At present there is no international standard for the T-bar and ball tests. One conclusion of the work in the research project, on which this paper is based, is the recommendation for using a T-bar of 40 mm diameter and 250 mm length. For the ball it is recommended that its diameter should be 112.9 mm giving a projected area of 100 cm^2. Speed during penetration and extraction should be the same as for penetration of the CPTU: 2 cm/sec. Normally the cone part of the penetrometer is replaced with the T-bar so that the same load cell as that used to measure cone resistance for the CPTU is used to measure the T-bar resistance. Figure 3 shows a picture of the three penetrometers. It should be mentioned that the research project also has given recommendations for cyclic T-bar testing that can be used to gain information on the remoulded shear strength (RANDOLPH [10]). Some examples of cyclic T-bar tests are given in the following.

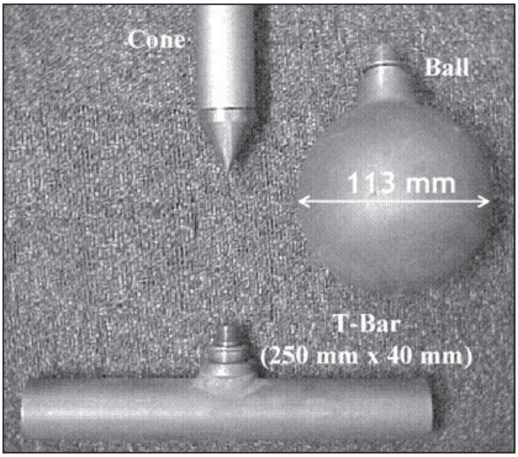

Fig. 3. CPTU, T-bar and ball

4. RESULTS OF IN SITU TESTS

Onsøy

Figure 4 shows the results of the five ENVI memocone CPTUs carried out at the Onsøy site. The individual values of the sleeve friction f_s, corrected cone resistance q_t, and penetration pore pressure u_2 from each test are shown in shaded form, while the average profiles are shown in bold. Figure 5 shows the results of altogether four T-bar profiles carried out using the ENVI memocone. Again the individual test results are shown shaded and the overall average in bold. Note that also penetration resistance during extraction of the T-bar has been measured, although this value has not been used in the following.

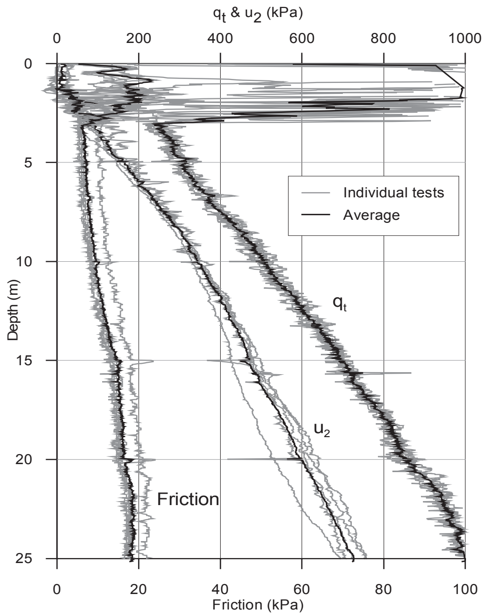

Fig. 4. Results of CPTUs carried out at Onsøy

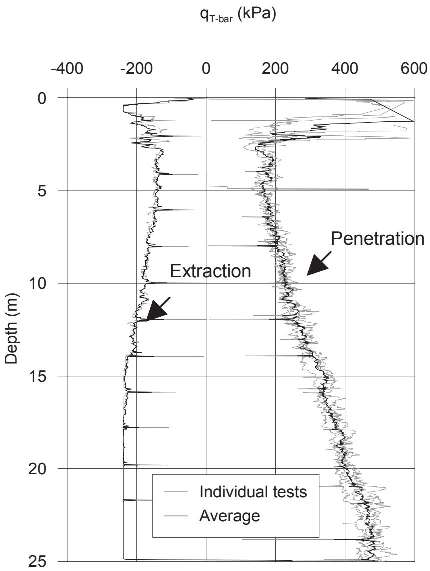

Fig. 5. Results of T-bar tests at Onsøy

Figure 6 gives the results of ball tests carried out at Onsøy (from YAFRATE and DEJONG [13]). Figure 7 compares average results from the CPTU's at Onsøy (expressed as $q_{net} = q_t - \sigma_{v0}$) with $q_{T\text{-bar}}$ and q_{ball}. It can be observed that $q_{T\text{-bar}}$ and q_{ball} are very similar and lower than q_{net}.

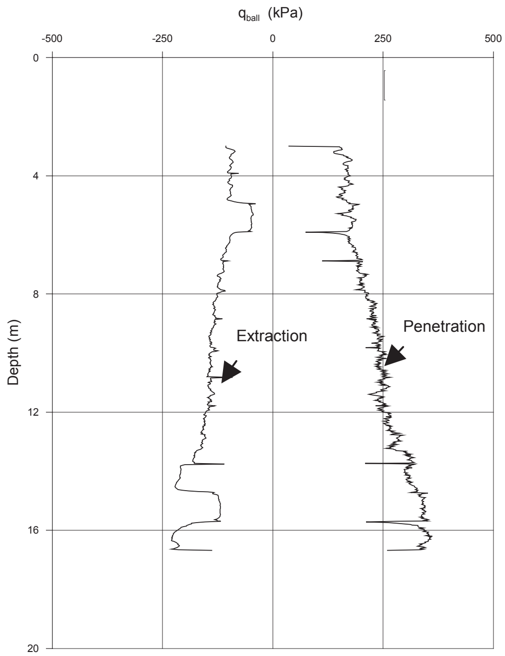

Fig. 6. Results of ball tests at Onsøy

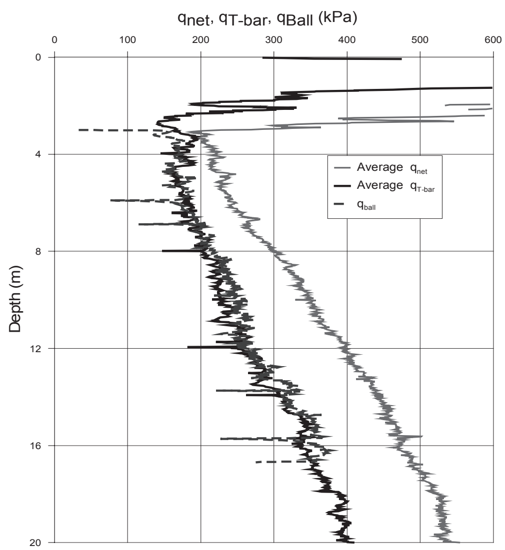

Fig. 7. q_{net}, $q_{T\text{-bar}}$ and q_{ball} vs depth, Onsøy

Figure 8 shows the results of cyclic T-bar and ball tests at Onsøy (from YAFRATE and DEJONG [13]).

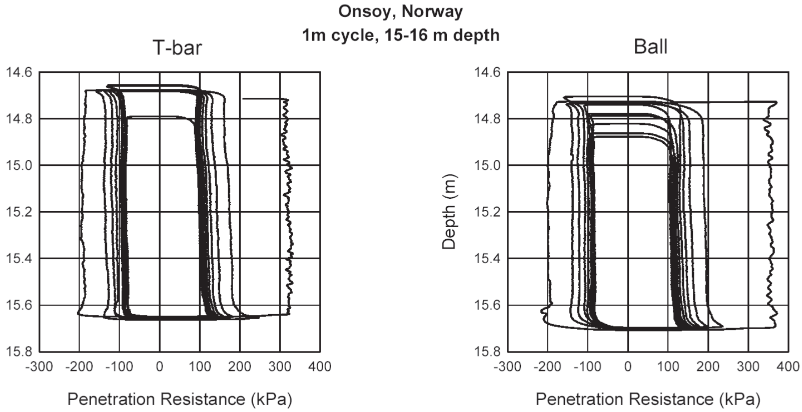

Fig. 8. Results of cyclic T-bar and ball tests at Onsøy (from YAFRATE and DEJONG [13])

Burswood

Figure 9 shows the results of two CPTU profiles in terms of f_s, q_t and u_2. CPTU No. 1 is 25 m from the sample boring and the T-bar tests, while the CPTU No. 2 is close to the sample borehole. Therefore the results of CPTU No. 2 have been used in

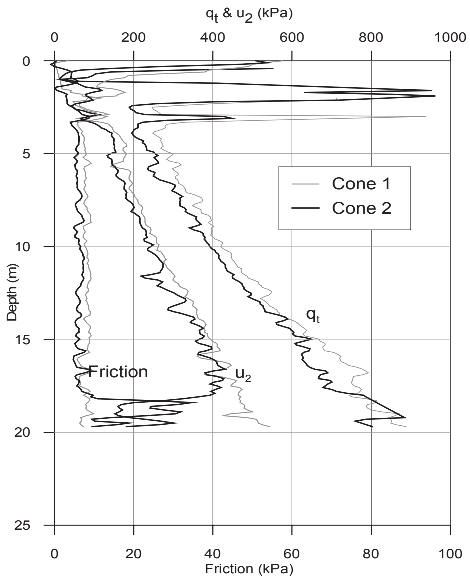

Fig. 9. Results of CPTUs carried out at Burswood (from LUNNE et al. [9])

the analyses described in the next chapter. Figure 10 shows the results of 4 T-bar tests in shaded form and the calculated average profile. Again the extraction profiles have been included. The lower sections of two of the profiles are caused by cyclic T-bar tests carried out. These have been excluded when calculating the average profile.

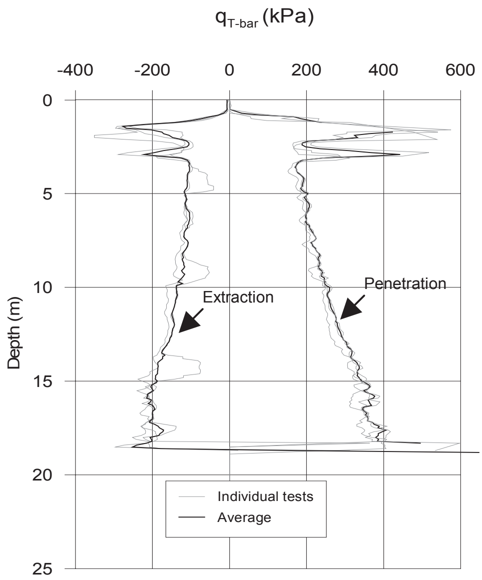

Fig. 10. Results of T-bar tests at Burswood (from LUNNE et al. [9])

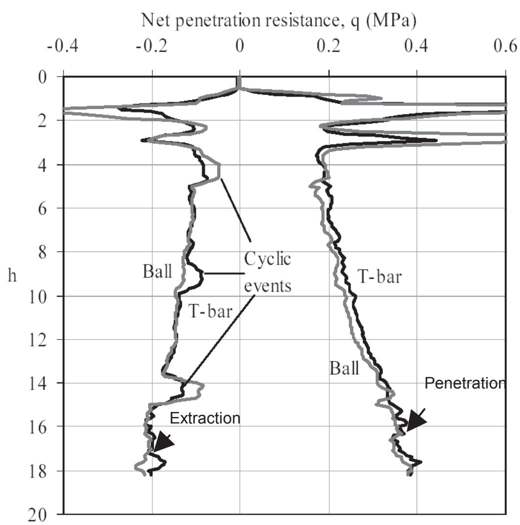

Fig. 11. Comparison of results of T-bar and ball tests at Burswood (after CHUNG and RANDOLPH [1])

Figure 11 shows the results of both T-bar and ball at Burwood. It can be observed that as for Onsøy the results from the two tests are very similar.

Comparison of CPTU and T-bar results at the three sites

Figures 12 to 14 give for all the three sites the ratio of the average values of $q_{\text{T-bar}}$ and q_{net}, $q_{\text{T-bar}}$ and Δu and finally Δu and q_{net}, where $q_{\text{net}} = q_t - \sigma_{v0}$. It is interesting to note that $q_{\text{T-bar}}/q_{\text{net}}$ tends to decrease with depth for Burswood, whereas for Onsøy this ratio is almost constant with depth. $\Delta u/q_{\text{net}}$ (which is equal to the pore pressure ratio B_q) profiles are below a depth of about 7 m, more or less constant for all three sites. The ratio of $q_{\text{T-bar}}/\Delta u$ follows the same trends as $q_{\text{T-bar}}/q_{\text{net}}$. It may be a potential to use the ratios shown in figures 12 to 14 to evaluate differences in soil properties including, but not limited to: OCR, rigidity index and strength anisotropy. This item is under further study by NGI and COFS.

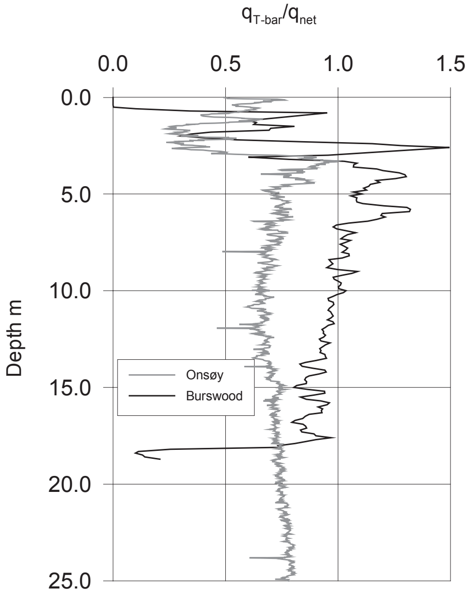

Fig. 12. $q_{\text{T-bar}}/q_{\text{net}}$ vs depth for Onsøy and Burswood (after LUNNE et al. [9])

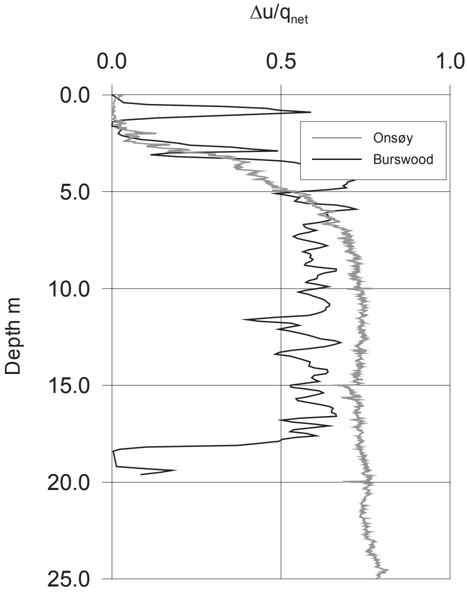

Fig. 13. $\Delta u/q_{\text{net}}$ vs depth for Onsøy and Burswood (after LUNNE et al. [9])

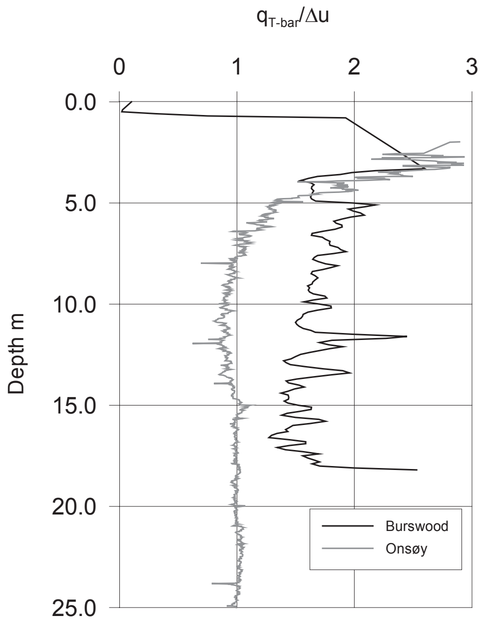

Fig. 14. $q_{\text{T-bar}}/\Delta u$ vs depth for Onsøy and Burswood (after LUNNE et al. [9])

5. CORRELATIONS

For the CPTU the undrained shear strength s_u can be computed either from the net cone resistance or from the excess penetration pore pressure using the following formulas:

$s_u = (q_t - \sigma_{v0})/N_{kt}$ where σ_{v0} is the total vertical stress and N_{kt} is a cone factor.

$s_u = (u_2 - u_0)/N_{\Delta u}$, where u_0 is the in situ static pore pressure and $N_{\Delta u}$ is another cone factor.

Even though the above two expressions are theoretically based, there are so many simplifications and assumptions involved in these theories that it is commonly accepted that the cone factors have to be determined empirically. Numerous correlation studies have been carried out in the past giving quite a range in the cone factors (e.g., LUNNE et al. [6]). One major issue is which value of s_u to use. In the past, NGI has mostly used the undrained shear strength determined by a CAUC (anisotropically consolidated undrained) triaxial test sheared in compression, s_u^{CAUC}. In the following the average undrained shear strength from a CAUC and a CAUE (sheared in extension) s_u^{CAUE} and a direct simple shear test s_u^{DSS} have also been used. The average s_u has been denoted by $s_{u,av} = 1/3(s_u^{\text{CAUE}} + s_u^{\text{CAUE}} + s_u^{\text{DSS}})$.

As mentioned in the introduction, the T-bar and ball are full flow penetrometer types so that it is not necessary to subtract the total vertical stress when computing s_u, thus the T-bar factor $N_{\text{T-bar}}$ becomes:

$$s_u = q_{\text{T-bar}}/N_{\text{T-bar}}.$$

Similarly

$$s_u = q_{\text{ball}}/N_{\text{ball}}.$$

Since the T-bar and ball resistances are very similar for the tests done at both Onsøy and Burswood, we have in the following only included cone and T-bar factors.

Theoretical work done in the present project has shown that even if theories exist for how to interpret the T-bar and ball in terms of undrained shear strength parameters, there are so many assumptions that are required in the analyses that the $N_{\text{T-bar}}$ and N_{ball} factors have to be determined empirically as for the cone penetrometer (RANDOLPH and ANDERSEN [11]). The remarks about the s_u value to use in the correlations are valid for the T-bar and ball as well.

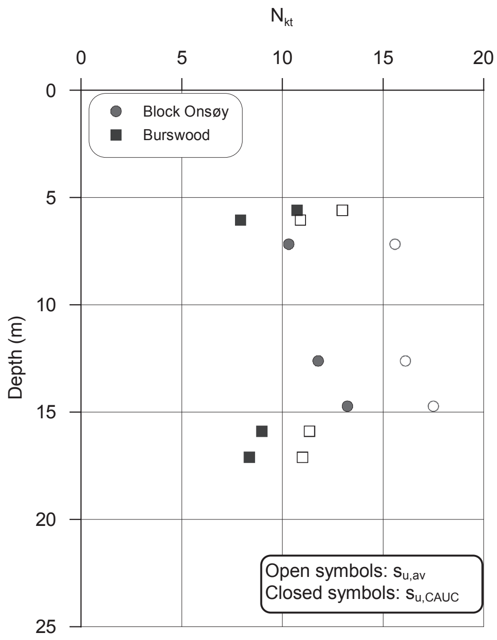

Fig. 15. N_{kt} vs depth (after LUNNE et al. [9])

Figures 15, 16 and 17 show computed values of N_{kt}, $N_{\Delta u}$ and $N_{\text{T-bar}}$ vs depth for Onsøy and Burswood clays, respectively. The open symbols refer to s_u^{CAUC} and the filled symbols to $s_{u,av}$.

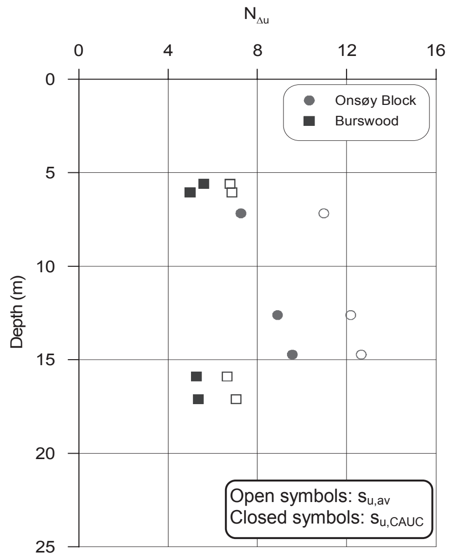

Fig. 16. $N_{\Delta u}$ vs depth (after LUNNE et al. [9])

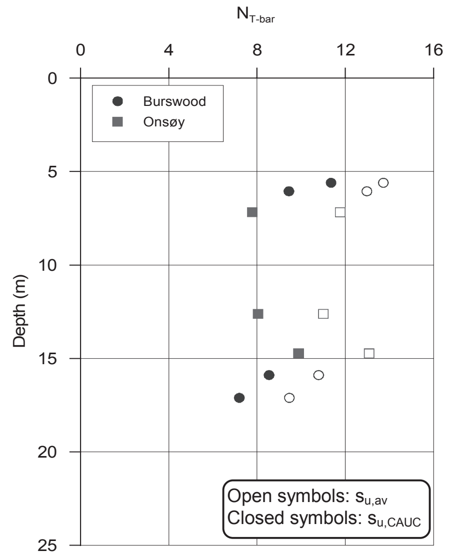

Fig. 17. $N_{\text{T-bar}}$ vs depth (after LUNNE et al. [9])

Tables 1 and 2 summarize the cone and T-bar factors shown in figures 15–17. The number of laboratory tests at each of the two sites are still quite limited, therefore the ranges of the factors have been given instead of the standard deviation. Although the number of values is relatively small there are some trends that are emerging:

• There is significant scatter in both the N_{kt}, $N_{\Delta u}$ and $N_{\text{T-bar}}$ values for the individual data points both within each site and between the sites. The range in average values for the two sites is, however, smaller.

• The range in the average $N_{\text{T-bar}}$ factors for the two sites is somewhat smaller than for the cone factors N_{kt} and $N_{\Delta u}$ and tend to imply that $N_{\text{T-bar}}$ may vary slightly less than N_{kt} and $N_{\Delta u}$ from one clay to another.

• The range or scatter in T-bar and cone factors based on $s_{u,av}$ is generally only slightly smaller than when based on $s_{u,\text{CAUC}}$.

Table 1

Summary of cone and T-bar factors based on $s_{u,\text{CAUC}}$

Site	N_{kt}		$N_{\Delta u}$		$N_{\text{T-bar}}$	
	Average	Range	Average	Range	Average	Range
Onsøy	11.7	10.3–13.2	8.6	7.3–9.5	8.6	7.8–9.9
Burswood	8.6	8.0–10.2	5.3	5.0–5.7	9.2	7.2–11.7
Overall	10.2	8.0–13.2	7.0	5.0–9.5	8.9	7.2–11.7

Table 2

Summary of cone and T-bar factors based on $s_{u,av}$

Site	N_{kt}		$N_{\Delta u}$		$N_{\text{T-bar}}$	
	Average	Range	Average	Range	Average	Range
Onsøy	16.4	15.6–17.5	11.9	11.0–12.6	12.0	11.0–3.1
Burswood	11.5	11.0–12.6	7.0	6.7–7.3	11.4	9.5–13.5
Overall	13.9	11.0–17.5	9.5	6.7– 2.6	11.7	9.5–13.5

6. RECOMMENDATIONS

The findings in the previous chapter have been used to arrive at the recommended values given in table 3.

Table 3

Recommended CPTU and cone factors

In situ test	Empirical factor	Undrained shear strength (kPa)	Recommended range
CPTU	N_{kt}	$s_{u,\text{CAUC}}$ $s_{u,av}$	9–13 12–17
	$N_{\Delta u}$	$s_{u,\text{CAUC}}$ $s_{u,av}$	6–9 7–12.5
T-bar	$N_{\text{T-bar}}$	$s_{u,\text{CAUC}}$ $s_{u,av}$	8–11 10–13

For the CPTU it is recommended that both corrected cone resistance q_t and excess pore pressure Δu should be used to compute either $s_{u,\mathrm{CAUC}}$ or $s_{u,av}$. Local experience may show that one cone factor works best for one particular clay. Whenever possible the undrained shear strength values should be supplemented with sampling and laboratory tests, and local correlations be developed.

A general comment for both the CPTU and T-bar factors is that when it is conservative to have a low value of s_u, like in bearing capacity calculations, then the upper values in the ranges in table 3 should be used. When it is conservative to have a high undrained shear strength, like in skirt penetration analyses, the lower ranges given in table 3 should be used. It should be mentioned that the recommended CPTU and T-bar factors given in table 3 have been based on experience from a rather limited range of clays, with the values of soil plasticity varying from 33 to 45%, and OCR from 1.8 to 1.3. It is clearly a need to expand the basis for the correlations, and especially there is a need to cover high-plasticity clays like those encountered offshore Africa.

The CPTU should be the basic in situ test for soil investigations, because of its excellent profiling capability and because of the large amount of experience for interpretation of soil type and a range of soil parameters.

However, when it is important to have as reliable undrained shear strength values as possible, it is recommended that T-bar and/or ball tests be carried out in addition to CPTU.

7. SUMMARY AND CONCLUSIONS

CPTU, T-bar and ball tests have been carried out at NGI's and COFS' onshore soft clay test sites in Onsøy, Norway, and Burswood, Australia. Triaxial and direct simple shear tests have been carried out on high-quality samples, so that the average undrained shear strength can be calculated: $s_{u,av} = s_{u,\mathrm{CAUC}} + s_{u,\mathrm{CAUE}} + s_{u,\mathrm{DSS}}$.

Correlation studies have been carried out whereby the cone factors N_{kt} and $N_{\Delta u}$ and the T-bar factor $N_{\text{T-bar}}$ have been computed based on both $s_{u,\mathrm{CAUC}}$ and $s_{u,av}$. It is indicated that T-bar factors are in a somewhat narrower range compared to cone factors. Recommendations are given in terms of cone and T-bar factors to use, and when T-bar tests should be carried out in addition to CPTU. For the Onsøy and Burswood clays the ball and T-bar resistances were very similar, hence for these clays it is appropriate to use $N_{\text{ball}} = N_{\text{T-bar}}$.

It is also recommended that similar correlations be developed also for other soils, and especially for high-plasticity clays.

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