

# Comparison of cone and T-bar factors in two onshore and one offshore clay sediments

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**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 has been introduced due to its potential for increasing the reliability of interpreted undrained shear strength relative to the CPTU for soft clays in deep waters. Empirical correlations based on field tests and laboratory tests on samples at one offshore and two onshore soft clay sites indicate 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.

## 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 (Lunne 2001).

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 due to hydrostatic water pressure, and the relatively small magnitude of the additional loads when penetrating soft soils. There are also difficulties with obtaining high quality undisturbed samples due to handling equipment in large water depths and also due to the large stress relief when samples are brought up to deck level. Damage to the soil structure can be especially severe if there is gas dissolved in the pore water, as the gas will come out of solution and expand due to the large stress relief (Lunne et al. 2001). Laboratory tests on soils that are disturbed in this way will result in measured soil parameters that are not representative of in situ conditions.

In situ tests that can give reliable soil parameters are therefore needed. Recently the T-bar has been introduced to offshore soil investigations (Randolph et al. 1998, Randolph 2004). The T-bar has a larger area, giving higher resolution in the measured penetration

resistance. The other advantage of the T-bar is that it is a so called ‘full-flow’ penetrometer, so 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 and T-bar 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 to undrained shear strength measured by triaxial and direct simple shear tests carried out on high quality samples. Results from one site offshore Australia have also been used in the correlations, in addition to some laboratory model tests at NGI and centrifuge tests by COFS.

## 2 DESCRIPTION OF SITES AND REFERENCE SOIL PARAMETERS

### 2.1 *Onsøy test site, Norway*

The onshore soft clay site at Onsøy has been used by NGI for more than 30 years. It is described in detail by Lunne et al. (2003). [Figure 1](#) shows a soil profile

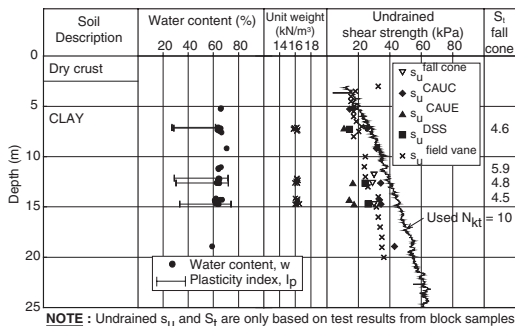


Figure 1. Soil profile Onsøy test site.

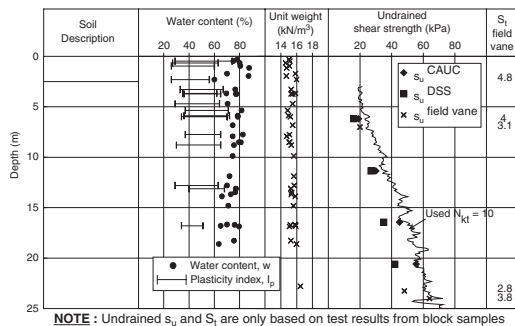


Figure 3. Soil profile at Laminaria site (to be completed).

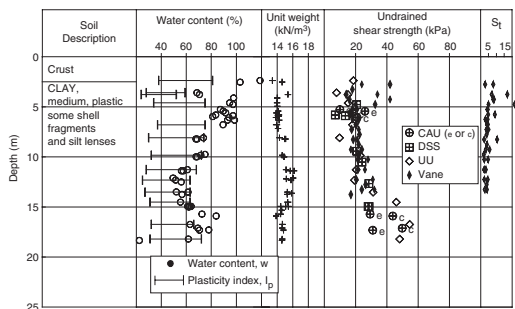


Figure 2. Soil profile Burswood test site.

close to the location where the CPTUs and T-bar 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 & Poulin 1979). Reconstituted Onsøy clay has also been used for some laboratory model tests where small-scale T-bar tests have been carried out. This will be further discussed in Section 5.

### 2.2 Burswood test site, Australia

An onshore soft clay site at Burswood (Perth) is used by the University of Western Australia 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 and 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. Reconstituted Burswood clay has also been used for centrifuge tests carried out at by COFS, with model CPTs and T-bar tests carried out on the centrifuge samples as discussed in Section 5.

### 2.3 Laminaria site, offshore Australia

The tests at this site in the Timor Sea offshore Australia were carried out as part of a site investigation for field development (Randolph et al. 1998). Figure 3 shows a soil profile at Laminaria. The reference CAUC and DSS tests were carried out on 76 mm diameter piston tube samples, whose quality will be less good than the block samples at Onsøy. CAUE tests were not carried out on the Laminaria samples.

## 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 1999). In particular the tests at NGI have been done with the ENVI memocone, the tests at Burswood with the Hogentogler cone penetrometer and the tests at the Laminaria site with the Fugro 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. For the Laminaria tests pore pressures were measured on the cone tip,  $u_1$ .

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 net cone resistance,  $q_{net}$  and the excess pore pressure,  $\Delta u$ .

At present there is no international standard for the T-bar test. One conclusion of the work in the JIP on which this paper is based, is the recommendation to use a T-bar 40 mm in diameter and 250 mm long, thus giving a projected area 10 times that of the standard cone. The penetration and extraction rate should be the same as for the CPTU, i.e. 20 mm/s. Normally the cone part of the penetrometer is replaced with the T-bar so that the same load cell as used to measure



Figure 4. Picture of cone penetrometer and T-bar used at Onsøy.

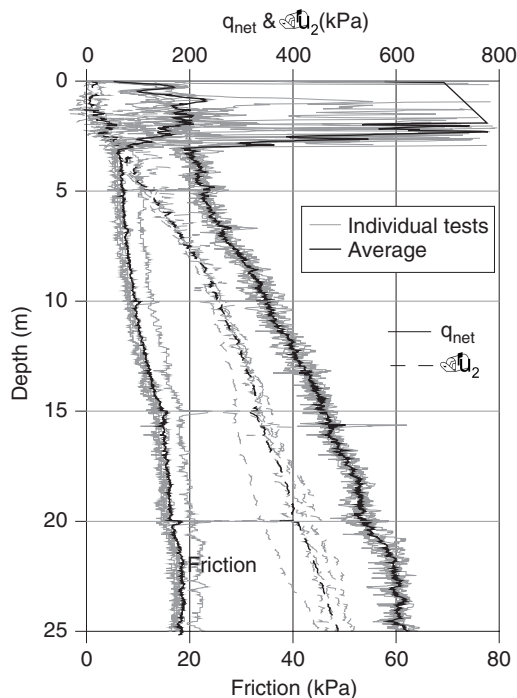


Figure 5. Results of CPTUs carried out at Onsøy.

cone resistance for the CPTU is used to measure the T-bar resistance (Fig. 4).

The project has also given recommendations on cyclic T-bar testing that can be used to get information on the remoulded shear strength (see Randolph 2004). However, the present paper does not include results from this part of the programme.

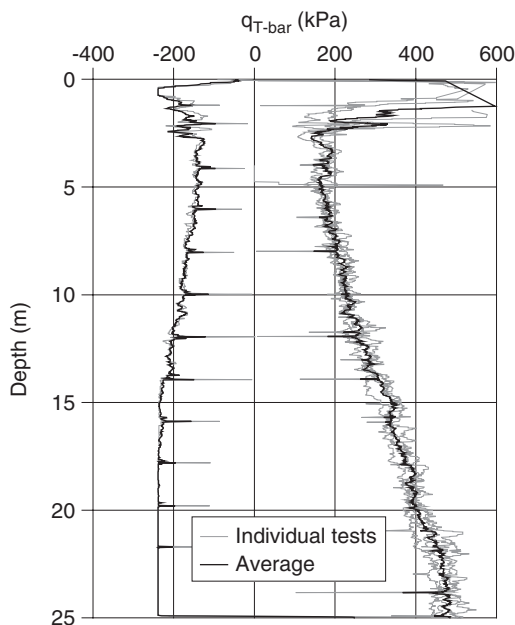


Figure 6. Results of T-bar tests carried out at Onsøy.

## 4 RESULTS IN SITU TESTS

### 4.1 Onsøy

Figure 5 shows the results of the five ENVI memocone CPTUs carried out at the Onsøy site. The individual values of 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 6 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 the resistance during extraction of the T-bar has also been measured, although these values are not discussed further in this paper.

### 4.2 Burswood

Figure 7 shows the results of two CPTU profiles in terms of  $f_s$ ,  $q_t$  and  $u_2$ . CPTU 1 is 25 m from the sample boring and the T-bar tests, while CPTU 2 is close to the sample borehole. Therefore the results of CPTU 2 have been used in the analyses described in the next section. Figure 8 shows the results of 4 T-bar tests in shaded form and the calculated average profile. Again the extraction profiles have been included. The reductions in extraction resistance in two of the profiles, at depths of 4, 9 and 14 m, are due to cyclic T-bar tests having been carried out. These have been excluded when calculating the average profile.

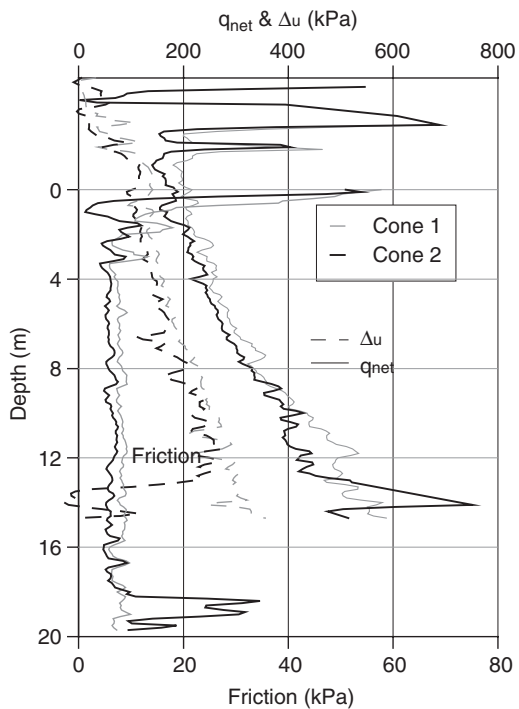


Figure 7. Results of CPTUs carried out at Burswood.

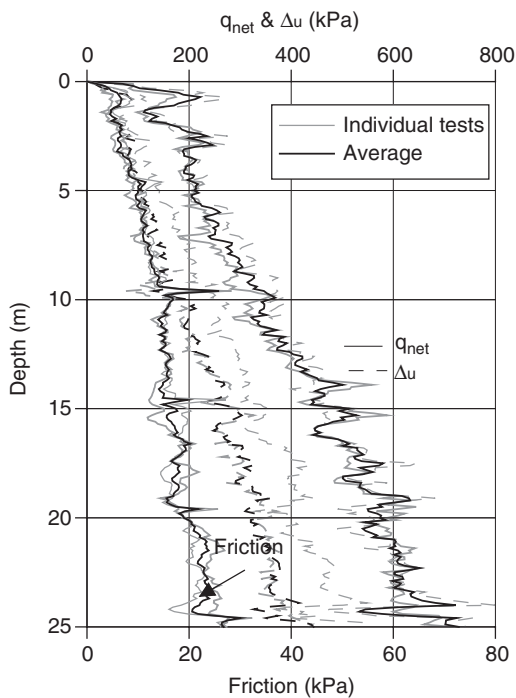


Figure 9. Results of CPTUs carried out at Laminaria.

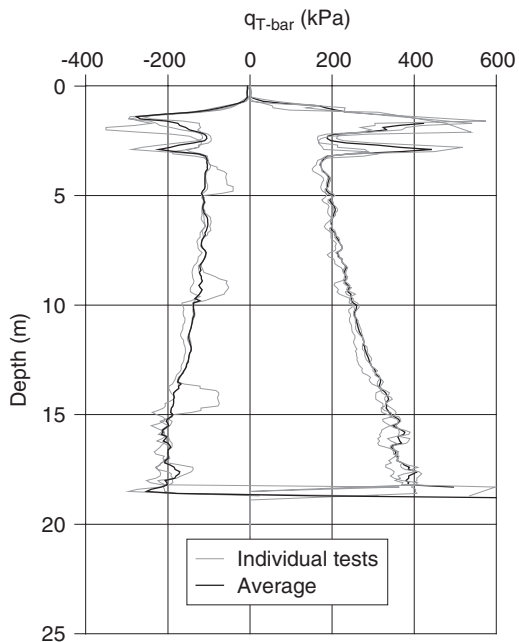


Figure 8. Results of T-bar tests carried out at Burswood.

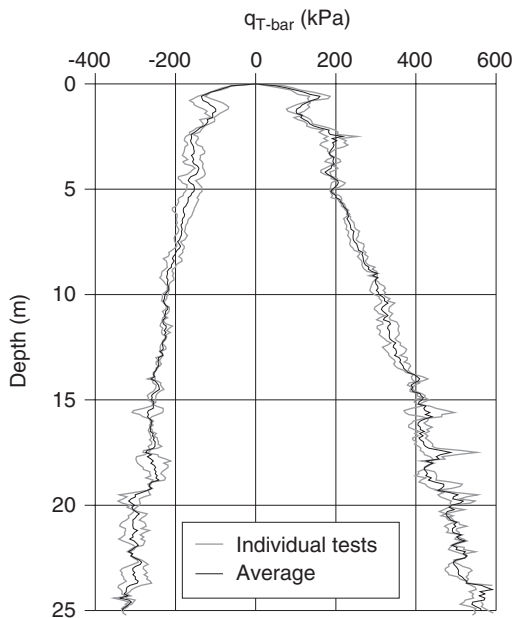


Figure 10. Results of T-bar tests carried out at Laminaria.

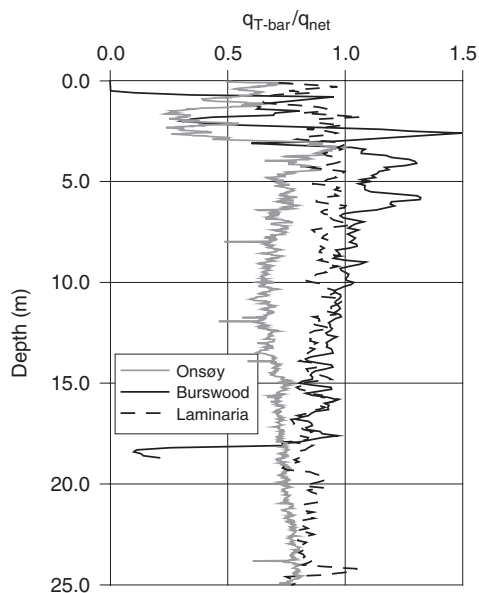


Figure 11.  $q_{T\text{-bar}}/q_{\text{net}}$  vs depth.

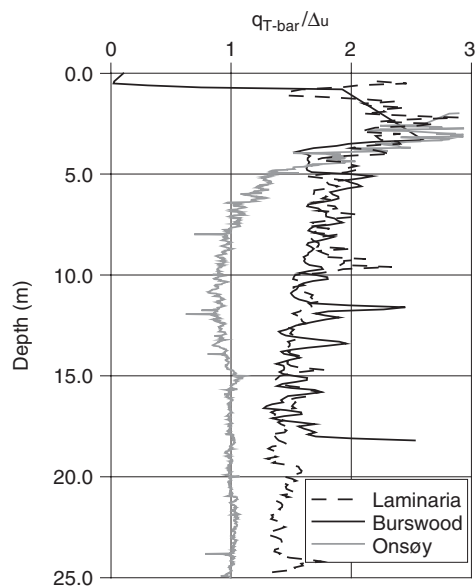


Figure 12.  $q_{T\text{-bar}}/\Delta u$  vs depth.

#### 4.3 Laminaria

Figure 9 shows two CPTU  $f_s$ ,  $q_t$  and  $u_1$  (measured on cone tip) profiles and the average of the two profiles. Figure 10 shows the results of two individual T-bar profiles and the computed average.

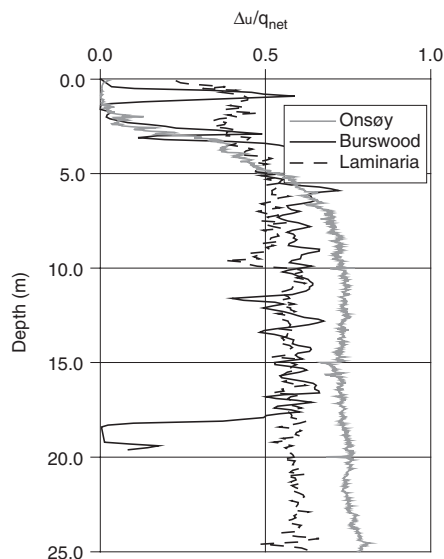


Figure 13.  $\Delta u/q_{\text{net}}$  vs depth.

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

Figures 11 to 13 give for all three sites the ratios of the average values of  $q_{T\text{-bar}}$  and  $q_{\text{net}}$ ,  $q_{T\text{-bar}}$  and  $\Delta u$  (from CPTU), and finally  $\Delta u$  and  $q_{\text{net}}$ , where  $q_{\text{net}} = q_t - \sigma_{vo}$ . It is interesting to note that  $q_{T\text{-bar}}/q_{\text{net}}$  tends to decrease with depth for Burswood and Laminaria, whereas for Onsøy this ratio is about constant with depth. The pore pressure ratio,  $B_q = \Delta u/q_{\text{net}}$ , profiles are more or less constant for all three sites below a depth of about 7 m, and so the ratio  $q_{T\text{-bar}}/\Delta u$  follows the same trends as  $q_{T\text{-bar}}/q_{\text{net}}$ . The ratios in Figures 11 to 13 may potentially be used to evaluate differences in soil properties such as: OCR, rigidity index and strength anisotropy. This is being explored further in a joint ongoing study by NGI and COFS.

### 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:

$$s_u = (q_t - \sigma_{vo})/N_{kt} \tag{1}$$

where  $\sigma_{vo}$  is the total vertical stress and  $N_{kt}$  is a cone factor

$$s_u = (u_2 - u_0)/N_{\Delta u} \tag{2}$$

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 (Lunne et al. 1997). 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  $s_{u,av} = (s_u^{CAUE} + s_u^{CAUE} + s_u^{DSS})/3$ .

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

$$s_u = q_{T-bar} / N_{T-bar} \tag{3}$$

Theoretical work done in the present project has shown that although theories exist for how to interpret the T-bar in terms of undrained shear strength parameters, there are many assumptions that are required in the analyses (Randolph & Andersen 2005).

As such empirical correlations for the  $N_{T-bar}$  factor are still required at present, just as for the cone penetrometer. However, the simplicity of the flow mechanism around the T-bar offers the potential for analytical solutions that take account of secondary soil characteristics such as strain rate dependency, strain softening and so forth. The remarks about the  $s_u$  value to use in the correlations are valid for the T-bar also, although the symmetry of the failure mechanism makes it more logical to correlate the T-bar resistance with the average strength,  $s_{u,av}$ .

Figures 14, 15 and 16 show computed values of  $N_{kt}$ ,  $N_{\Delta u}$  and  $N_{T-bar}$  vs depth for Onsøy, Burswood and Laminaria clays respectively. The open symbols refer to  $s_u^{CAUC}$  and the filled symbols to  $s_{u,av}$ .

Tables 1 and 2 summarize the cone and T-bar factors shown in Figures 14 to 16. The number of laboratory tests at each of the three sites are still quite limited, therefore the range 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:

- 1 There is significant scatter in both the  $N_{kt}$ ,  $N_{\Delta u}$  and  $N_{T-bar}$  values for the individual data points both within each site and between the sites. The range in average values for the various sites is, however, smaller.
- 2 The range in the average  $N_{T-bar}$  factors for the various sites is somewhat smaller than for the cone factors  $N_{kt}$  and  $N_{\Delta u}$ , implying that  $N_{T-bar}$  may vary less for different sites than  $N_{kt}$  and  $N_{\Delta u}$ .

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

Other work in the JIP project (NGI/COFS 2002) can also shed light on the T-bar factors. In connection with some pipeline-seabed model tests at NGI, T-bar tests were carried out using a small T-bar (20 mm in dia;

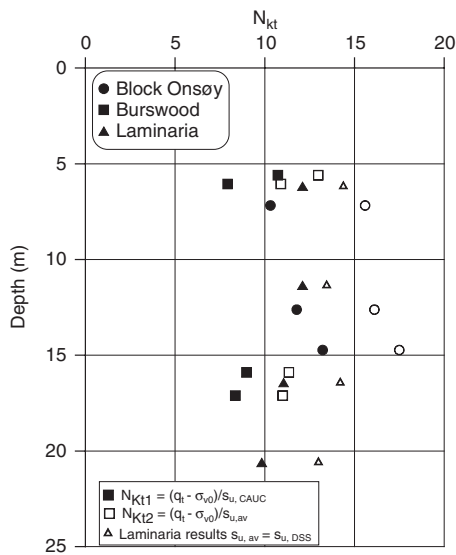


Figure 14.  $N_{kt}$  vs depth.

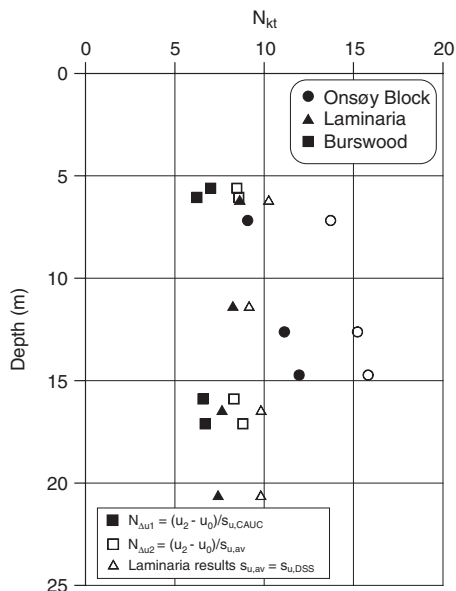


Figure 15.  $N_{\Delta u}$  vs depth.

125 mm long). These tests have been done on reconstituted Onsøy clay, and also on reconstituted clay from Watchet Harbour (UK). Reference shear strengths have been evaluated from plate load tests (Onsøy clay) and UU triaxial tests (Watchet Harbour clay).

Classification parameters for the Watchet Harbour and Onsøy clays are compared in Table 3.

In addition COFS has carried out centrifuge tests on reconstituted Burswood clay with ‘in flight’ mini-

ature T-bar tests (5 mm in dia; 20 mm long). Reference shear strengths have been determined by laboratory DSS tests.

Table 4 summarises the  $N_{T\text{-bar}}$  factors evaluated from the NGI model tests and the COFS centrifuge tests. For the tests on reconstituted Onsøy clay the shear strength has been corrected to be valid for  $s_{u,av}$  as defined above.

The  $N_{T\text{-bar}}$  factors listed in Table 4 are within the range of values obtained from the field tests based on  $s_{u,av}$  (Table 2) of 9.5 to 14.3 and give some confidence that the T-bar factors are also applicable for shallow soils.

## 6 RECOMMENDATIONS

The findings in the previous chapter have been used to arrive at the recommended values given in Table 5.

For the CPTU it is recommended that both the net cone resistance,  $q_t - \sigma_{vo}$ , and excess pore pressure

Table 3. Soil classification and index parameters for reconstituted Watchet Harbour (WH) and Onsøy clays.

Parameter	WH clay	Onsøy clay
Fines content (% < 0.002 mm)	35%	40%
Plasticity index	42%	30%
Water content	69 to 73%	60 to 65%
Sensitivity (from fall cone)	2.5	3,4
Shear strength at clay surface	3.2 kPa	1.5 kPa
Shear strength at 200 mm depth	6.0 kPa	4 kPa

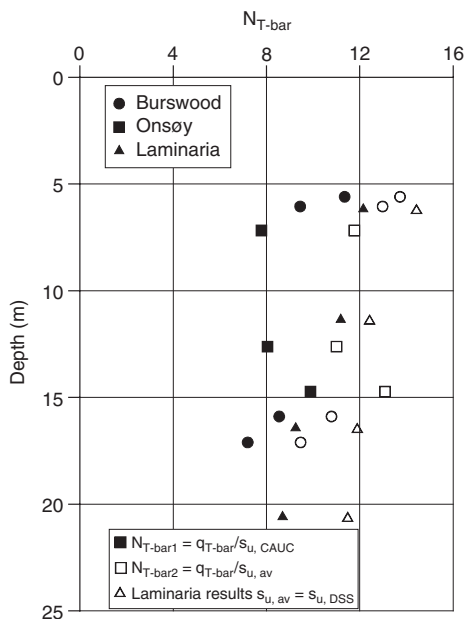


Figure 16.  $N_{T\text{-bar}}$  vs depth.

Table 1. Summary of cone and T-bar factors based on  $s_{u,CAUC}$ .

Site	$N_{kt}$		$N_{\Delta u}$		$N_{T\text{-bar}}$	
	Avg	Range	Avg	Range	Avg	Range
Onsøy	11.7	10.3–13.2	8.6	7.3–9.5	8.6	7.8–9.9
Burswood	8.6	8.0–9.7	5.3	5.0–5.7	9.2	7.2–11.7
Laminaria	11.3	10.0–12.5	N/A	N/A	10.2	8.8–12.1
Overall	10.5	8.0–13.2	7.0	5.0–9.5	9.3	7.2–12.1

Table 2. Summary of cone and T-bar factors based on  $s_{u,av}$ .

Site	$N_{kt}$		$N_{\Delta u}$		$N_{T\text{-bar}}$	
	Avg	Range	Avg	Range	Avg	Range
Onsøy	16.4	15.6–17.5	11.9	11.0–12.6	12.0	11.0–13.1
Burswood	11.5	11.0–12.6	7.0	6.7–7.3	10.6	9.5–11.6
Laminaria	13.7	12.9–14.8	N/A	N/A	12.4	11.6–14.3
Overall	13.9	11.0–17.5	9.5	6.7–12.6	11.7	9.5–14.3

should be used to compute either  $s_{u,CAUC}$  or  $s_{u,av}$ . Local experience may show that one cone factor works better for a given clay. Whenever possible the undrained shear strength values should be supplemented with

Table 4.  $N_{T-bar}$  factors from model tests.

Case	$N_{T-bar}$ avg	$N_{T-bar}$ range
NGI tests, Onsøy clay	11.9	11.0–13.4
NGI tests, WH clay	13.0	–
Centrifuge tests (Burswood)	10.2	9.7–10.7

Table 5. Recommended CPTU and cone factors.

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

Table 6. Applicability of interpreted soil parameters.

Geotechnical problem	Depth range (m)	Soil parameters required	Applicability <sup>1</sup>	
			CPTU	T-bar
Backfilled trenches: upheaval buckling <sup>2</sup>	0–1	• Soil profile	1–2	3
		• Classification	2	–
		• Soil density	2–3	–
		• Undrained strength	2–3	1–2
Pipeline and riser interaction with soil <sup>3</sup>	0–3	• Soil profile	1–2	3
		• Classification	2	–
		• Undrained strength	2	1–2
		• Remoulded strength	4	1–2 <sup>4</sup>
Skirted foundations: penetration, capacity	0–15 or 40 <sup>5</sup>	• Soil profile	1–2	3
		• Classification	2	–
		• Undrained strength	2	1–2
		• Remoulded strength	4	1–2 <sup>4</sup>
Seabed templates: penetration, stability, settlements	0–10	• Soil profile	1–2	3
		• Classification	2	–
		• Undrained strength	2	1–2
		• Remoulded strength	5	1–2 <sup>4</sup>
Geohazards Slope stability	0–10 or 100 <sup>5,7</sup>	• Settlements	(3–4) <sup>6</sup>	(–) <sup>6</sup>
		• Soil profile	1–2	3
		• Classification	2	–
		• Undrained strength	2	1–2
		• Remoulded strength	3–4	1–2 <sup>4</sup>

Notes:

1. Authors' views on relative applicability of tool, with scale: 1 High; 5 Very low; – not applicable.
2. Extremely soft soil may be encountered.
3. Very soft soil may be encountered.

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 5 should be used. When it is conservative to have a high undrained shear strength, like in skirt penetration analyses, the lower values given in Table 5 should be used.

It should be emphasised that the recommended CPTU and T-bar factors given in Table 5 have been based on experience from a rather limited range of clays, with values of soil plasticity varying from 33 to 45%, and OCR 1.8 to 1.3. There is clearly a need to expand the basis for the correlations, especially to cover high plasticity clays like those encountered offshore Africa.

The CPTU should be the basic in situ test for offshore 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 to also carry out T-bar tests in addition to CPTU as summarized in Table 6 below.

## 7 SUMMARY AND CONCLUSIONS

CPTU and T-bar 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, with an average undrained shear strength calculated as the arithmetic mean of triaxial compression, direct simple shear and triaxial extension strengths.

Results of similar tests have also been made available from the Laminaria soft clay site offshore Australia, except that CAUE tests were not carried out so that the average strength was taken as the simple shear strength.

Correlations studies have been carried out whereby the cone factors  $N_{kt}$  and  $N_{\Delta u}$  and the T-bar factor  $N_{T\text{-bar}}$  have been computed based on both  $s_{u,CAUC}$  and  $s_{u,av}$ . It was found that T-bar factors lay in a somewhat narrower range compared to cone factors. Provisional recommendations are given in terms of what cone and T-bar factors to use, and when T-bar tests should be carried out in addition to CPTUs.

It is also recommended that there is a need to develop similar correlations also for other soils, especially the high plasticity clays as are found offshore Africa.

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Watchet Harbor clay tests were made available from the STRIDE JIP managed by 2H Offshore.

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