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Full-flow CPT tests in a nearshore organic clay

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ABSTRACT: The T-bar is a full-flow CPT with a larger probe surface area compared with the conventional CPT probe. The tip has the shape either of a ball or as an upside-down T, a so-called T-bar. The term 'full-flow' comes from the assumption that the earth 'flows' around the tip, which is a realistic assumption for soils with extremely low undrained shear strength. This paper presents a case study where a large number of T-bar tests have been performed in a nearshore organic clay with high water content and very low undrained shear strength. The test site is located in Stockholm, Sweden, where planned land reclamation and capping of contaminated top soils are challenging from a stability perspective due to the low strength of the soil. T-bar tests were thus performed to characterise the shear strength profile of the soil in detail, especially at shallow depths where sampling was difficult and the shear strength values were under 5 kPa. A N-factor relating the net cone resistance (q_{net}) and the undrained shear strength of the soil (c_u) was evaluated based on T-bar measured parameters and direct simple shear tests and undrained triaxial tests on samples taken at greater depths. This allowed to estimate shear strength profiles with depth. For all tests, both the penetration and extraction cone resistance were measured, and a good correlation was obtained between this ratio and the soil sensitivity measured in the laboratory. In addition, the sensitivity was correlated to the organic content of the clay. These correlations were found to be OCR-dependent. Further, cyclic tests were performed, and their results were correlated with the remoulded shear strength values. This facilitated mapping of the soil conditions across the site.

1 INTRODUCTION

Conventional CPT tests have long been used in all types of soil to interpret strength characteristics. In extremely soft clays the penetration resistance is however very small, and hence full-flow penetration tests was developed during the late 1990s, mainly for offshore applications (Stewart & Randolph, 1994; Randolph, 2004). The full-flow probe has the shape of a ball or a upside-down 'T' in order to increase its probe area and hence the penetration resistance.

The probe area is normally enlarged 10 times compared to conventional CPT tests. As the full-flow probe is mounted on conventional CPT probe, only replacing the tip, the probe area is 10 times larger than the drilling rod. This gives several advantages in extremely soft soils:

– The penetration resistance is 10 times higher, i.e. the meaurement uncertianties originating from the load cell decrease
– The correction of overburden stress and pore pressure measurements are one tenth, i.e. they are almost negligable
– The resistance can be measured during penetration and extraction, giving additional data on soil type and behaviour

This paper presents a case study where full-flow CPT tests have been performed nearshore as part of a land reclamation project. An old industrial area, located in the northeastern part of central Stockholm, is undergoing residential development. Highly contaminated soils are also planned to be capped, i.e. a fill layer is placed on the seabed to minimize dispersion of contamination. The soil consists of extremely soft organic clay and gyttja, and hence the filling is challenging from a stability persective. The full-flow CPT tests were performed to obtain high-quality detailed strength properties, especially in the upper part of the soil. In addition, the area had local variation due to earlier unknown works such as dregding, and hence mapping of the nearshore area

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was important. The full-flow CPT tests was shown to be an excellent method to quickly map the area, as a complement to sampling and laboratory testing.

2 BACKGROUND

2.1 *Previous work on full-flow CPT tests*

The full-flow CPT tests have been used during the last 20 years for field applications (e.g., Yafrate *et al.*, 2009; Peuchen & Terwindt, 2016; Nakamura *et al.*, 2009; Boylan *et al.*, 2011; Schaeffers & Weemees, 2012), as well as in laboratory tests including centrifuge tests (Almeida *et al.*, 2011; Levacher *et al.*, 2016; Sahdi *et al.*, 2014). In addition, the full-flow test has been analysed theoretically by e.g. Randolph & Andersen (2006) and Zhu et al. (2020).

In Sweden, a research project on sensitive clays on land was performed around 10 years ago (Larsson *et al.*, 2014; Åhnberg & Larsson, 2012). The purpose was to investigate cyclic strength degradation of highly sensitive and quick clays.

Randolph (2004), DeJong *et al.* (2010) and Lunne *et al.* (2011) provide excellent all-inclusive description of the method.

2.2 *Correction of tip resistance*

Similar as for the conventional CPT test, the measured tip resistance is corrected by overburden stress and measured pore pressure. This corrected tip resistance (q_{net}) is calculated by Eq. 1 (DeJong *et al.*, 2010):

$$q_{net} = q_c - [p_o - u_2(1-a)]\frac{A_s}{A_P} \tag{1}$$

where q_c = measured tip resistance; p_0 = total vertical overburden stress; u_2 = measured pore pressure, a = area ratio, A_s = area of rod; and A_p = tip area. This equation assumes that the soil ‘flows’ around the probe and applies a vertical stress on the upper surface. As the ratio $A_s/A_p \approx 0.1$, the effect of overburden stress and pore pressure is one tenth of that for conventional CPT tests. It is thus often negligible.

2.3 *Evaluation of shear strength*

The undrained shear strength (c_u) is calculated as:

$$c_u = \frac{q_{net}}{N_{Tbar}} \tag{2}$$

Usually, site specific calibrations are recommended, however, the N_{Tbar} factor normally is found to be around 10-13 (Lunne *et al.*, 2011; DeJong *et al.*, 2010). It is found to be dependent on soil type, sensitivity and rate of strain softening.

Figure 1. The Iskymeter (top left), column penetration test (top right) and T-bar used in this study (bottom). The T-bar was Ø40 mm and width 250 mm (tip area 10,000 mm^2). The drilling rod is Ø36 mm (area ~1,000 mm^2) Sources: Kallstenius (1961), Massarsch (2014), Geotech (2019).

According to theoretical studies by Randolph & Andersen (2006) the N_{Tbar} is in the range 11-13, not noticeably dependent on strength anisotropy if the average strength is used. For cyclic tests, i.e. several cycles of penetration and extraction over an interval, a remoulded strength can be interpreted with a N_{Tbar} varying between 10.5-15.

Larsson *et al.* (2014) studied 13 different Swedish soils and found that N_{Tbar} was highly dependent on the soil’s plasticity, in particular its liquid limit. A range between ~7 for low-plastic soils to ~16 for high-plastic soils were found.

2.4 *Comparison with similar tests*

Although the shape of the T-bar probe is unique, there are two other penetration tests which are remarkably similar. The ‘Iskymeter’ was developed by the Swedish Geotechnical Institute during the 1930s for soft clays. The Iskymeter consists of two foldable wings which are folded during penetration and unfolded when extracted where the extraction resistance is measured. Calibration of shear strength was done by comparing extraction resistance, fall cone test and in situ vane tests, and a N-factor of around 10-15 was found, dependent on both sensitivity and organic content (Kallstenius, 1961).

The Iskymeter is no longer in use but was supposedly the origin for the column penetration tests which is used as a quality control of dry deep mixing columns. For this application, a N-factor of 10 is used (Axelsson, 2001), but this has undergone surprisingly little research.

Photographs of the Iskymeter, the column penetration and T-bar probe are shown in Figure 1. Notably, the Iskymeter, the standard dimension column penetration test and the full-flow CPT have equal probe areas, i.e. 10,000 cm^2. The N-factor for interpretation of shear strength is also similar.

2.5 *Extraction ratio*

The extraction ratio for full-flow CPT tests, i.e. ratio between penetration (q_{in}) and extraction (q_{out}) resistance is often used to interpret the soil's sensitivity. For low sensitive soils, the ratio is typically 0.6-0.8 decreasing to around 0.3 for highly sensitive soils (DeJong *et al.*, 2010).

3 SITE AND METHODS

3.1 *Soil profile*

Figure 2 shows a typical soil profile in one of the boreholes with a water depth of ~18 m. The sediments consist of clayey gyttja from seabed down to appr. 10 m depth. From around 10 m the soil is categorised as clay. As the organic content and water content decreases with depth, the density increases.

The plastic limit is normally not determined in Swedish engineering practice. Instead, only the liquid limit is used for empirical correlations, including silt and organic content. Figure 3 shows values of liquid limits vs. organic content from tests on the soil profile shown in Figure 1. This correlation allows a simple mapping of soil type only by liquid limit values.

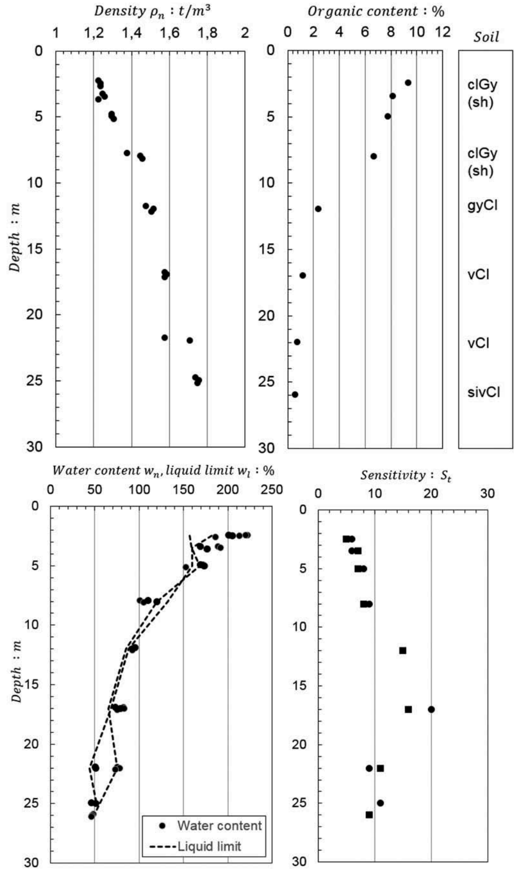

Figure 2. Typical soil profile (water depth ~18 m). cl = clay, gy = gyttja, sh = shales, v = varved, si = silt. Soil classification according to EN ISO 14688-1 and -2.

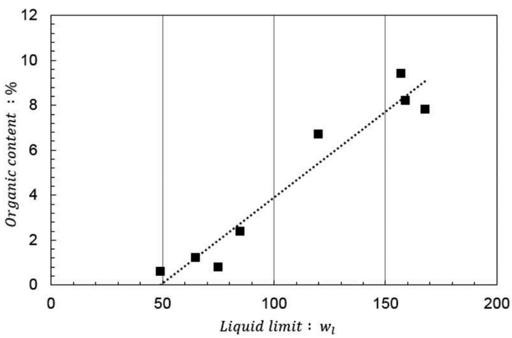

Figure 3. Liquid limit vs. organic content on samples from borehole shown in Figure 1.

3.2 *Execution of the field work*

The nearshore area had limited water depths, and all tests and sampling were done using a pontoon with supporting legs as a stable working platform. A total of around 30 T-bar tests were performed in an area of around 400x500 m. However, only a few is presented herein due to limited space. Around half was done with data acquisition also during extraction, and a few was performed with cyclic tests.

All T-bar tests were performed with the drilling rod within a casing to prevent excess deflection of the rod. Divers attached the T-bar probe under the casing, and also noted the time of penetration into seabed.

Sampling was done using the standard Swedish piston sampler (50 mm and 60 mm diameter).

3.3 *Laboratory tests*

A total of around 40 samples were retrieved. Routine analyses, i.e. bulk density, natural water content, liquid limit and intact and remoulded shear strength with fall cone (FC) tests were performed on all samples.

On selected samples, CRS oedometer, direct simple shear (DSS) and triaxial compression and extension tests were performed.

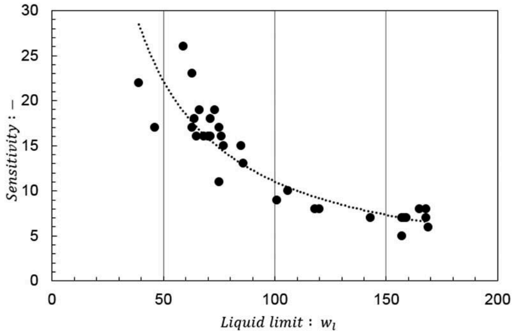

Figure 4. Liquid limit vs. sensitivity on all samples.

4 RESULTS

4.1 *Evaluation of undrained shear strength*

The strength anisotropy is larger for silty clay than organic clay and gyttja. It was thus decided to calibrate the N_{Tbar} against the undrained direct simple shear strength (c_u^{DSS}). This eliminates any anisotropy effects in the penetration tests as it is done in a stratigraphy of both organic and silty clay (example in Figure 2). Interpreting the c_u^{DSS} is also normal practice for conventional CPT tests in Sweden.

Trials of correlating q_{net} with strengths from FC and DSS tests were done using several soil parameters, however, the N_{Tbar} was found to be best expressed as a function of the liquid limit. Notably, the liquid limit reflects the type of soil, its organic content and sensitivity (Figure 3 and 4). The following expression was evaluated:

$$N_{Tbar} \approx 5 + 10 \times w_L \tag{3}$$

w_L is here given in decimal form. A typical example of a strength profile with depth is shown in Figure 5. Here, Equations 1–3 gives strength values similar to FC and DSS tests. The figure also shows c_u^{DSS} calculated by empirical correlations with preconsolidation stress from CRS oedometer tests and c_u^{DSS} (Hov *et al.*, 2021). Figure 5 also shows results from triaxial tests at shallow depths, although these were not used for intepretation of the T-bar tests.

As seen in the figure, the strengths are extremely low just below the seabed, in practice zero at seabed, but increasing with around 1.2 kPa/m. By correlating the T-bar tests with laboratory data on greater depths, it is thought that a strength extrapolation towards the seabed is realistic. The T-bar tests seemed to confirm this. Obviously, strengths evaluations from full-flow tests are more certain than conventional CPT test due to the larger tip resistance, thus reducing the measurement uncertainties.

For normal ranges of liquid limits for inorganic clays, i.e. liquid limits around 40-80%, the N_{Tbar} varies between ~10 and ~13. These values are similar to those found by Larsson *et al.* (2014), Nakamura *et al.* (2009), Randolph & Andersen (2006) and others.

For higher values of liquid limits, i.e. organic clays and gyttja, the N_{Tbar} is up to ~20 according to Equation 3. This is in the same range as reported for tests in peat (e.g., Long & Boylan, 2012; Boylan *et al.*, 2011).

4.2 *Evaluation of sensitivty*

The extraction resistance was measured for several of the T-bar tests. An example is given in Figure 6 where both the extraction (q_{out}) and penetration (q_{in}) resistance is shown. The q_{out} is consistenly lower than q_{in}, as expected, due to the remoulding occuring around the probe.

Figure 7 plots all extraction ratios (q_{out}/q_{in}) vs. sensitivity values from laboratory FC tests where T-bar tests and sampling were done in the same location. The ratios varies between 0.45 and 0.9, decreasing with increasing sensitivity. This is in the same range as reported by e.g. DeJong *et al.* (2010) for low sensitive soils.

There is a clear correlation between the two variables, despite the relative small variation in sensitivity. This relationship is also seen in e.g. Yafrate *et al*. (2009). The correlation is however OCR-dependent (the OCR in the OC area is around 1.2–3).

4.3 *Evaluation of remoulded shear strength*

Cycles were performed in an attempt to correlate the penetration resistance with the remoulded strength measured in the laboratory (using FC tests). Cycles over 1 m intervals are shown in Figure 6, and a detailed resistance plot of the upper cycle is shown in Figure 8. This cycle was perfomed in clayey gyttja with a water content of 150–200%. A clear decrease in both penetration and extraction resistance is seen for each cycle.

Figure 9 plots the average penetration resistance (q_{in}) for each cycle vs. number of cycles. It seems that after 5-7 cycles, the decrease in resistance seems to level off. This is similar to the findings from e.g. Yafrate *et al.* (2009).

The measured remoulded undrained shear strength in the laboratory was 1.1 kPa. The N-factor in the clayey gyttja was thus evaluated to:

$$N_{Tbar,rem} \approx 35 \tag{4}$$

It should be noted that cycles were performed in a very limited number of locations, so the dependency of plasticity, sensitivity or OCR has not been evaluated.

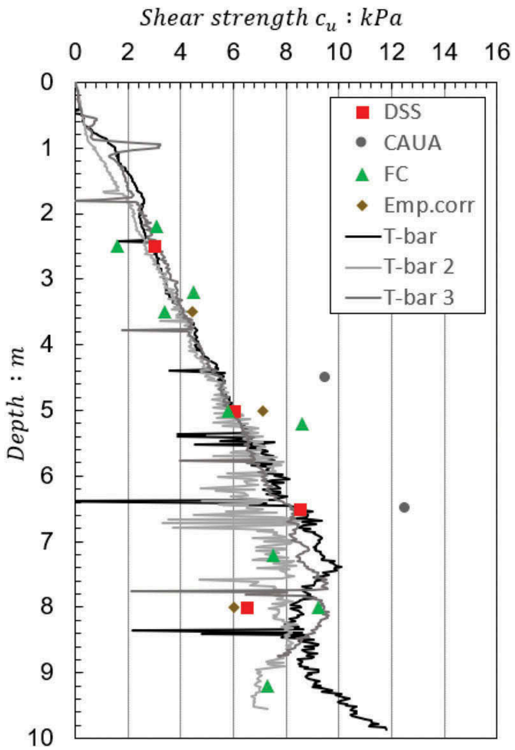

Figure 5. Typical example of evaluated strength by Eqs. 1-3 plotted together with results from laboratory tests. Strength "Emp.corr" is based on empirical correlations with the preconsolidation stress σ'_c from CRS oedometer tests; $c_u^{DSS} \approx (0.125 + 0.205 \times w_L) \times \sigma'_c$ for OCR=1,0-1,3 (Hov *et al.*, 2021).

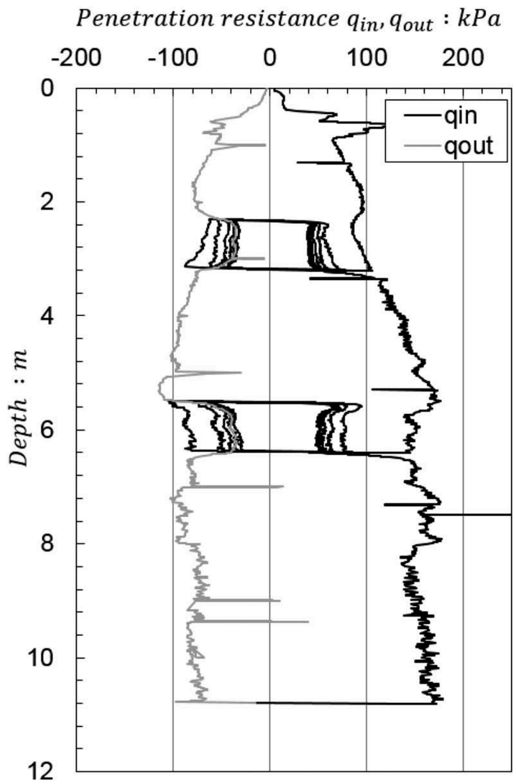

Figure 6. Typical example of penetration and extraction resistance in one T-bar test. Two sets of cycles were performed during penetration.

5 DISCUSSION

The T-bar tests were shown to be very useful for this type of project. The two main benefits were: a) detailed analyses of undrained shear strength in the upper part of the deposit, i.e. for strengths which in practice increases from zero, and b) a rough mapping of soil conditions by analysing the extraction ratio.

The very low strengths are difficult to measure with conventional CPT probes due to the large measurement uncertainty. In addition, sampling of such low strength sediments is very difficult, and in practice impossible with the Swedish piston sampler as it is dependent on soil resistance when coring (the coring is done by rotation of the drilling rods, but the outer part of the sampler is kept still using the soil resistance).

The use of T-bar tests showed that the strength increases almost linearly from zero at seabed. This was valuable information for stability evaluation of

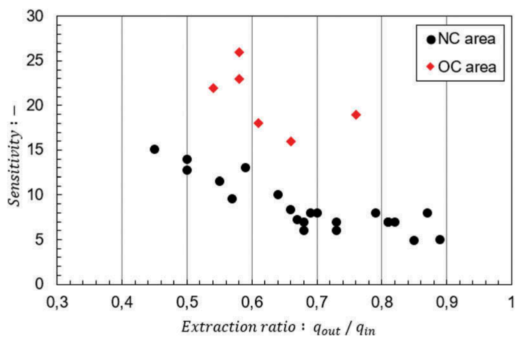

Figure 7. Values of sensitivity from laboratory tests (fall cone) and evaluation extraction ratio (example given in Figure 6).

the planned capping of the contaminated areas and filling for land reclamation.

The rough mapping of soil conditions was possible using the correlations between extraction ratio, sensitivity, liquid limit and organic content.

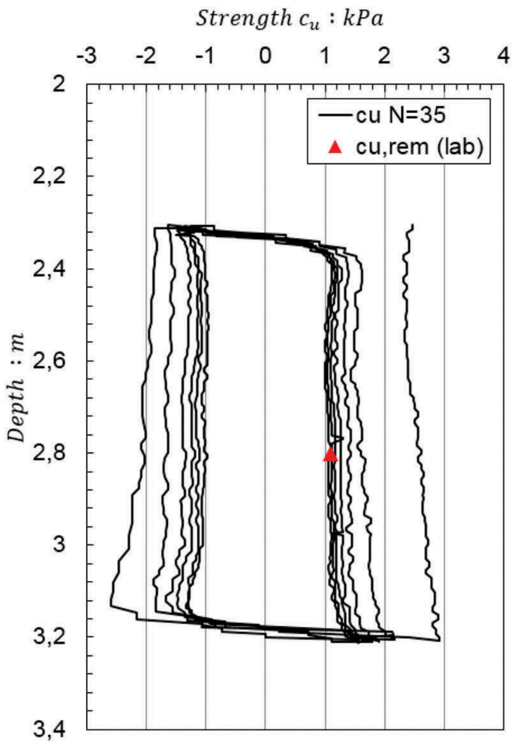

Figure 8. Example of cyclic test (upper cycle shown in Figure 6). Shear strength evaluated using N = 35. Negative strength is shown for extraction to make the figure more readable.

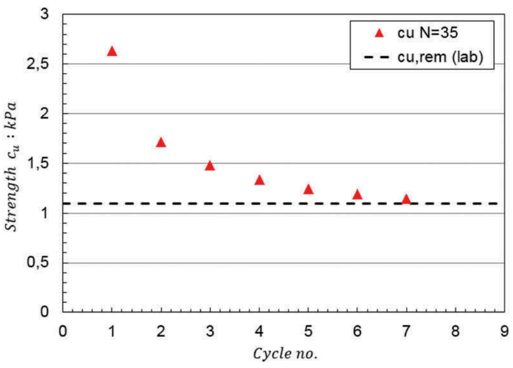

Figure 9. Measured strength using N=35 and remoulded strength from FC tests for cycle shown in Figures 7 and 8.

6 CONCLUSIONS

This paper presents a nearshore case study where a large number of T-bar tests have been performed. The sediments consisted of organic clay and gyttja. The following conclusions are drawn:

– The T-bar test is a useful testing equipment for soils with extremely low shear strengths,
– The N-factor was evaluated to vary between ~10 and ~20,
– The N-factor increases with increasing plasticity (i.e. liquid limit),
– A good correlation was obtained between the extraction ratio and sensitivity,
– A N-factor of around 35 was found for cyclic tests to evaluate the remoulded shear strength.

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