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Critical appraisal of T-bar penetration tests

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ABSTRACT: Deployment experience and metrological assessment indicate an overvalued applicability of the T-bar penetration test (TBT) as an offshore in situ test. More attention should be given to a combination of ball penetration tests (BPT) and cone penetration tests (CPT). Reasons for reducing TBT preference include: (1) no axial symmetry of T-bar, which promotes unwanted directional drift and associated bending influence on measurements, (2) sensitivity to torsional forces acting on T-bar, giving undetectable measurement error, (3) limited opportunity for enhanced test interpretation from pore pressure data. The current ratio of offshore TBTs to BPTs is about 10:1 to 100:1 when expressed in metres penetration. A reversal of the TBT:BPT ratio would be prudent, as BPTs rate better. This is supported by uncertainty analysis for penetration resistance q_m according to ISO 19901-8, possibly representing a first-ever calculation.

1 INTRODUCTION

This paper focuses on the T-bar penetration test (TBT) as in situ test. It excludes miniature versions of the TBT used for testing of soil samples on site or in a geotechnical laboratory.

The TBT involves measurement of the resistance of ground to continuous penetration at a steady slow rate of a cylindrical rod (T-bar penetrometer) positioned perpendicular to the lower end of push rods (Figure 1). A T-bar penetrometer is equipped with internal sensors, the output of which is recorded at least every second, at a nominal penetration rate of 20 mm/s ± 5 mm/s. The measurements comprise penetration length, penetration resistance and inclination from vertical. Optional measurements can include penetration resistance during retraction, cyclic penetration resistance and pore pressure. The ball penetration test (BPT) is equivalent to the TBT except that the T-bar is replaced by a sphere. Figure 1 shows T-bar and ball penetrometers with optional button filters for pore pressure measurement. A cone penetrometer with a cross sectional area of 1000 mm^2 is shown for comparison of scale.

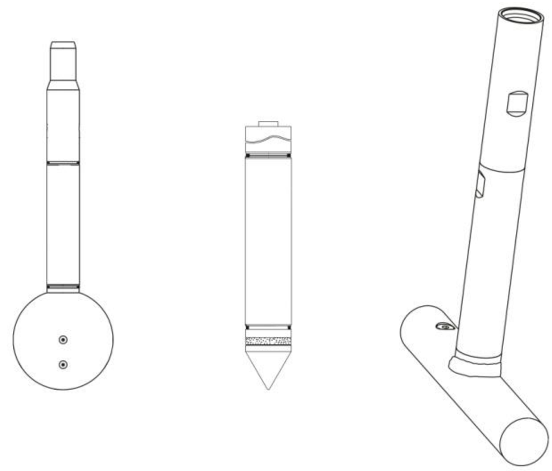

Figure 1 Fugro T-bar, cone and ball penetrometers.

In practice, TBT and BPT systems are comparable to cone penetration test (CPT) systems. The T-bar or ball is in place of the cone part of the cone penetrometer. The geometry differences lead to differences in characterisation of soil behaviour, primarily related to displacement and flow of soil around a cone with the same cross sectional area as the shaft and push rods versus flow of soil around a T-bar+shaft or ball+shaft.

The in situ version of the TBT was first used in Australia during 1996 (Randolph et al. 1998). It quickly gained offshore industry recognition as a profiling tool for deepwater soft clays. Its offshore use has been fairly steady over the past 10 years, with an annual guestimate in the order of 2 km total penetration. The ratio of TBT to CPT is in the order of 0.03 in terms of penetration metres, considering offshore use. Onshore use of the TBT is almost entirely for research purposes. This ratio for combined onshore and offshore penetration metres is possibly in the order of 0.002. The current ratio of offshore TBTs to BPTs is about 10:1 to 100:1

2 INTERNATIONAL STANDARDISATION

ISO 19901-8 (2014) and EN (2015) provide requirements and recommendations for offshore TBTs and BPTs. EN (2015) is a copy of ISO 19901-8. This paper will further refer to ISO 19901-8.

ISO 19901-8 considers TBTs and BPTs to be "particularly suitable for characterizing very soft to soft clays and clayey silts with an undrained shear strength < 50 kPa". In practice, this suitability or applicability corresponds to normally consolidated profiles of fine grained soils to depths in the order of 35 m below seafloor, or shallower for overconsolidated profiles.

The allowable minimum accuracy for measurement of penetration resistance q_m is 5% or 20 kPa, whichever is larger. This means that the changeover from 20 kPa to 5% is at q_m = 400 kPa, which corresponds with an undrained shear strength of about 40 kPa. Note that minimum accuracy is a *requirement* of ISO 19901-8, i.e. mandatory for compliance. Metrological confirmation should be done according to ISO (2003). This is a *recommendation*, i.e. not mandatory. The following comments are offered.

1 To the knowledge of the authors, the requirements for accuracy of q_m were set based on a general uncertainty estimate. No uncertainty estimate according to ISO (2003) was published prior to first issue of ISO 19901-8 and, probably, this paper.
2 The accuracy requirements for q_m apply to downward penetration. ISO 19901-8 considers upward retraction and cyclic test phases as optional possibilities.
3 The parameter q_m is uncoupled from depth below seafloor. ISO 19901-8 considers depth accuracy classes Z1 to Z5, with allowable accuracy values ranging between 0.1 m and >2 m. Z4 (2 m) is the default accuracy class.
4 The terms error and accuracy are used. These terms can lead to interpretative differences in practice. Error implies a reference quantity value. This probably refers to a value determined in a calibration laboratory or similar, as it is generally impossible to obtain an in situ reference value. Accuracy assumes knowledge of a true value, i.e. what should be regarded as true value.
5 True values depend on permissible equipment-specific and procedure-specific features. This means that compliance with ISO 19901-8 only provides a first indication of accuracy required for geotechnical practice. Further processing can be necessary to obtain fit-for-purpose accuracy, i.e. accuracy that is independent of equipment and procedures. To the knowledge of the authors, such benchmarking is yet to be demonstrated.

Further requirements of ISO 19901-8 include a nominal penetration rate of 20 mm/s ± 5 mm/s and data recording at 1 Hz or more. Further recommendations of ISO 19901-8 include a "standard" T-bar with a length of 250 mm and diameter of 40 mm and a minimum ratio of 7:1 for the projected cross sectional area of the T-bar to the cross sectional area of the push rod. This ratio suits use of a modified CPT cone penetrometer for TBTs. BPT recommendations are equivalent to those for the TBT. ISO 19901-8 gives no requirements for pore pressure measurement.

3 UNCERTAINTY ESTIMATION FOR PENETRATION RESISTANCE

Figure 2 shows example results of uncertainty $|U_{qm}|$ analysis for q_m according to ISO 19901-8, possibly representing a first-ever calculation. The figure includes a comparison with CPT cone resistance q_c $|U_{qc}|$. The results confirm TBT and BPT benefits in accuracy when considering the upper few metres below seafloor. The benefits primarily relate to sensitivity of a penetrometer load cell to transient temperature change. The example calculations consider uncertainties from 2 °C initial temperature difference between seabed temperature and seawater temperature just above seafloor as well as additional heat generated by frictional work. The larger area of a T-bar or ball, compared to a cone, mitigates such uncertainties. The benefits reduce with increasing penetration resistance and penetration depth, particularly after a penetrometer has acquired a stable temperature environment.

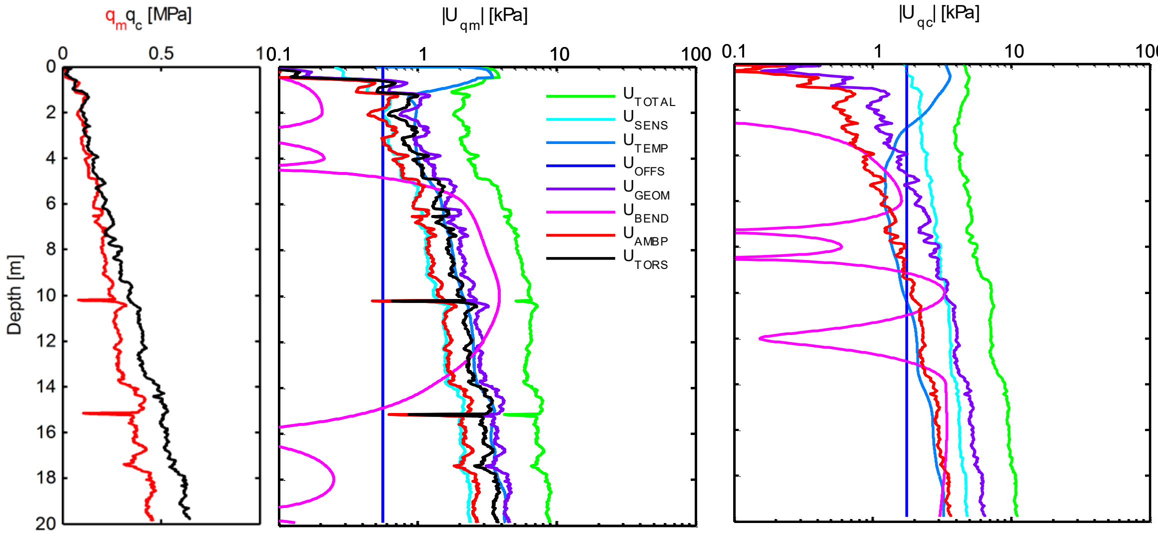

Figure 2 Examples of uncertainty estimates for high-quality TBT and CPT systems and practices, non-drilling deployment and water depth of 1500 m.

The selected approach is according to a published method for CPT cone resistance q_c (Peuchen & Terwindt 2015):

$$U_{TOTAL} = k \cdot \sqrt{\left(c_1 \frac{U_1}{d_1}\right)^2 + \left(c_2 \frac{U_2}{d_2}\right)^2 + \ldots + \left(c_i \frac{U_i}{d_i}\right)^2}$$

where U_{TOTAL} is parameter value uncertainty, k is a coverage factor, U_1 to U_i are estimated standard uncertainties, c_1 to c_i are sensitivity coefficients and d_1 to d_i are distribution coefficients. The selected value for k is 2, which corresponds to a 95% confidence interval. The selected value for the c-coefficients is 1, applicable to a linear relationship. The selected value for the d-coefficients is $\sqrt{3}$, which corresponds to an extreme value approach and a rectangular distribution. The component uncertainties cover sensor for force measurement U_{SENS}, geometry and dimensional errors of penetrometer U_{GEOM}, ambient and transient temperature influence U_{TEMP}, bending moment acting on penetrometer U_{BEND}, influence of water pressures acting on penetrometer U_{AMBP}, offset of measurements to seafloor as reference U_{OFFS}.

A CPT approach for TBTs and TBTs requires consideration of additional factors: definition of q_m and estimated uncertainty for axial torsion U_{TORS} affecting q_m.

The parameter q_m is partially defined by ISO 19901-8. In practice, q_m is assumed as the measured axial force divided by the maximum cross sectional area of the penetrometer. This assumption implies that (1) the cross sectional area for upward retraction is equal to the downward push and (2) q_m includes axial soil resistance on the fixed portion of the vertical connection between the horizontal part of the T-bar and the vertical part of the T-bar that has no effect on force measurement. The influence of these assumptions can be ignored for uncertainty estimates according to ISO 19901-8.

Laboratory calibrations of penetrometers are generally for compressive loading. Limited experiments indicate that linearity of high quality load cells for cone penetrometers differ by up to a few percent when comparing compressive and tensile loading. Note that the load cell of a T-bar penetrometer often remains in compression during offshore retraction and cycling. For example, a T-bar would be just in compression for q_m = -250 kPa and a water depth in the order of 350 m.

U_{TORS} can be estimated according to $U_{TORS} = a \cdot b \cdot q_m$. The presented example results for U_{TORS} consider $a = 0.3\ kPa \cdot N^{-1} \cdot m^{-1}$ and $b = 2.75 \cdot 10^{-5}\ m^3$. The coefficient a represents laboratory experiments at $q_m = 0$, showing a linear response of apparent q_m to torsional load. The coefficient b represents an example proportion of axial force transferred to torsional load. Note that torsional measurement error remains undetectable during TBTs, when applying CPT load cell technology. The T-bar geometry contributes to torsional influence, as the penetrometer shape has no axial symmetry. This implies sensitivity to (1) development of torsion compared to CPTs and to a lesser extent BPTs, (2) non-vertical penetration and (3) cork-screw rotation in case of incomplete fixity to axial rotation of the push rods. Note that (3) can possibly imply that penetrometer retraction will be (partially) in undisturbed soil and that the number of cycles for obtaining nearly constant cyclic penetration resistance will increase.

It may be expected that U_{TORS} correlates significantly to bending U_{BEND}. Such correlation is currently not accounted for. U_{BEND} correlates to inclination of a penetrometer (Peuchen and Terwindt 2014). Figure 3 illustrates results of a brief review of inclination measurements. This brief review generally showed (1) comparable penetrometer inclination for normally consolidated clays to 20 m below seafloor and (2) potential for reducing bending forces during a cyclic TBT phase. The change in inclination (i) of Fig. 3 is shown by some but not all tests.

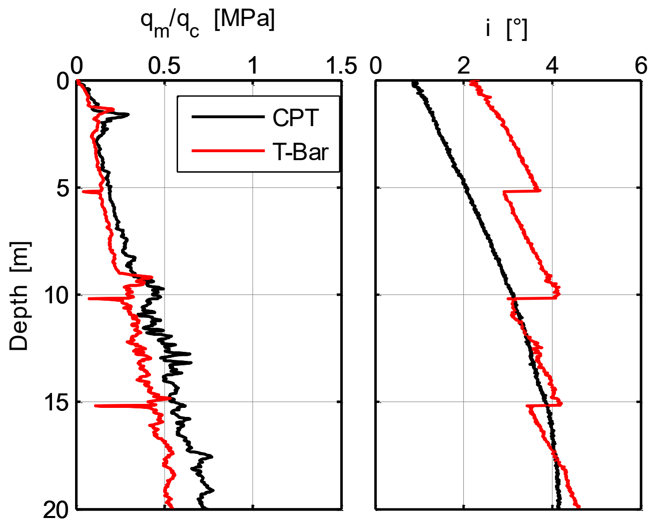

Figure 3 T-bar inclination changes during cyclic test stages compared to a cone penetration test; cyclic test stages are evident from low-value spikes in q_m profile.

4 ANALYTIC TBT AND BPT

It can be convenient to compare results against an Analytic test, rather than a test standard designed for practice (Peuchen and Terwindt 2014). The Analytic TBT would include a 250 mm long bar of 40 mm diameter with a "push rod of zero cross-sectional area". Similarly, the Analytic BPT would have a sphere of 113 mm diameter. The Analytic versions exist in computer models. They allow true full-flow of soil around a deeply embedded object, i.e. no material volume (e.g. push rod or soil) is introduced or withdrawn from the soil body during penetration. Similarly, modelling of shallow embedment is simplified when considering (1) formation of a cavity in soil during penetration and (2) "excavation" of soil during retraction (Fig. 4).

The Analytic TBT would render:

$$q_m = Q_p/A_1 = q_{T\text{-bar}} = q_T.$$

The parameter $q_{T\text{-bar}}$ (q_{ball}) is given by ISO 19901-8 as:

$$q_{T\text{-bar}} = Q_p/A_1 - (A_2/A_1)u_0 - (A_3/A_1)(\sigma_{vo} - u_0),$$

where:

A_1 = maximum cross sectional area of the penetrometer perpendicular to the axis of the push rod

A_2 = cross-sectional (steel) area at the push rod / penetrometer connection

A_3 = cross-sectional area of the push rod immediately above the penetrometer

Q_p = axially measured force on the penetrometer, positive for downward push

$q_{T\text{-bar}}$ = net penetration resistance for T-bar

u_o = hydrostatic pore pressure calculated for penetration depth z, relative to seafloor

σ_{vo} = total in situ vertical stress calculated for the horizontal axis of the T-bar, relative to seafloor.

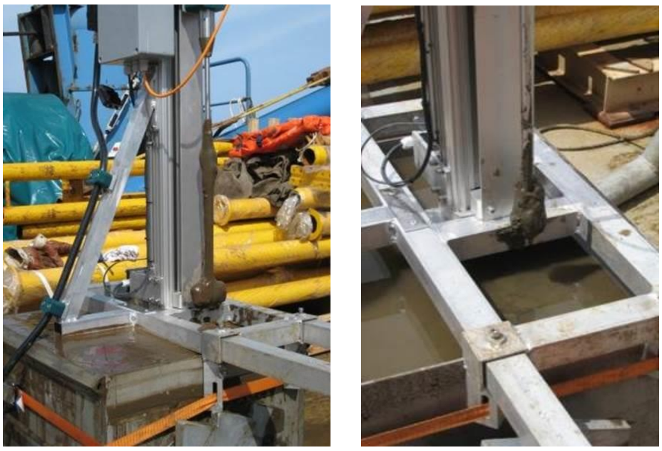
Figure 4 Soil adhering to mini T-bar penetrometer after retraction from offshore box core sample.

The equation for $q_{T\text{-bar}}$ is a simplification, in that pore pressure in the gap at the level of A_2 is replaced with u_0. The equation for $q_{T\text{-bar}}$ is based on Senneset et al. (1982), who relate net penetration resistance of a (cone) penetrometer to classical bearing capacity theory for a wished-in-place penetrometer in undrained soil. Robertson and Campanella (1983) added a correction for pore pressures that depends on (cone) penetrometer design, particularly net area ratio $a = A_2/A_1$.

5 COMPARATIVE COMMENTS FOR TBT, BPT AND CPT

TBT / BPT applicability applies to a narrow range of soil conditions compared to a wide range of soil conditions for CPTs. In practice, the range of soil conditions may be expressed in terms of q_m and q_c. Values for q_m are typically limited to 0.5 MPa to 1 MPa and values for q_c to 50 MPa to 100 MPa. These limits vary in practice, based on assessment of value of higher limits versus risk of loss or damage of equipment. The differences in limits to penetration resistance relate to push forces in kN required to penetrate a relatively large T-bar (ball) penetrometer plus push rods versus a relatively small cone penetrometer plus push rods. Risk of equipment damage and loss in heterogeneous soil also contributes to practical limits. The cone penetrometer has a favourable geometry for heterogeneous soil. The ball penetrometer is axi-symmetric, with a weak point at the connection with the vertical shaft. The T-bar penetrometer has no axial symmetry, as discussed above. It is less robust than the ball penetrometer.

TBT deployment is limited to non-drilling mode, whereby T-bar push and retraction are from a seafloor-based template. The 250 mm width of a T-bar precludes drilling mode. A miniature TBT for drilling mode deployment (i.e. through the drill string) was trialled and found to lack the robustness required for the typically onerous offshore operating conditions (Peuchen et al. 2005). The geometries of ball penetrometers and cone penetrometers allow both non-drilling and drilling modes, including wireline deployment down a borehole. Drilling mode enhances flexibility for testing as-found, heterogeneous soil conditions. Drilling modes include floating vessel, stable-non floating platform and seafloor drilling.

The above section on Uncertainty Estimation for Penetration Resistance illustrates that TBT/ BPT accuracy for penetration resistance is *slightly better* than for CPTs. This is contrary to popular beliefs: *much better*, *superior*. The halo effect for TBT and BPT accuracy is probably related to misunderstanding of metrology of load cells, particularly confusion between load cell range and hysteresis within the measuring range of interest rather than full scale output (Peuchen & Terwindt 2014).

Conventional CPT measurements (cone resistance, sleeve friction and pore pressure) allow excellent profiling for soil behaviour types. The TBT and BPT also allow for profiling for soil behaviour type if pore pressure sensors are incorporated. However, this is of limited interest because tests are generally done only in clays and clayey silts with undrained shear strengths of less than 50 kPa. Pore pressure measurements can be of interest for optional pore pressure dissipation and twitch testing. The ball penetrometer has the better qualifications compared to the T-bar (e.g. Mahmoodzadeh et al. 2015).

Interpretation of upward TBT results and cyclic test results should consider possible axial rotation of the T-bar relative to the downward push. Penetrometer retraction may be (partially) in undisturbed soil. Axial rotation may imply an increase in number of cycles for obtaining nearly constant cyclic penetration resistance. A ball penetrometer has axial symmetry. Any axial rotation is of little concern.

Interpretation of TBTs, BPTs and CPTs for undrained shear strength is empirical. Interpretation is similar in that it requires a range of considerations to account for equipment-specific differences and soil behaviour around complex penetrometer geometry. Correlation with undrained shear strength with T-bar or ball penetration resistance has a reduced influence of in situ effective stresses, in comparison with CPTs. This benefit appears to be obscured by other correlation issues, as indicated by a Joint Industry Project (NGI 2006) showing very close statistical comparison of TBT and CPT results in soft clays. It may be of interest to explore accuracy of undrained shear strength by comparing uncertainty estimates based on the Analytic versions of the TBT, BPT and CPT.

A particular consideration for TBT and BPT interpretation is partial flow of soil around the penetrometer, i.e. soil closure around the penetrometer except for the shaft. A gap in soil applies close to seafloor. The length of the zone with gap formation depends on soil strength and overconsolidation ratio. It can possibly exceed 1 m. The authors are not aware of specific measurements. A cone penetrometer requires an initial embedment for achieving full displacement conditions. This initial embedment is typically less than 0.2 m for cone resistance and pore pressure in very soft to soft clays and clayey silts.

TBTs and BPTs offer improved opportunity for characterising strength degradation upon soil disturbance compared to CPTs, if cyclic test phases are implemented. A cyclic test phase provides information for a single test zone. It requires interruption of downward penetration. Vessel time requirements are about 15 minutes per cyclic test. Selective, site-specific TBT or BPT cyclic test phases allow fine tuning of generalised correlations of remoulded undrained shear strength with continuous CPT profiling of sleeve friction f_s or corrected sleeve friction f_t. Note that ISO-type accuracy of f_s of a high quality cone penetrometer is in the order of ± 3 kPa (Peuchen and Terwindt 2015) for offshore non-drilling deployment in very soft to soft clays and clayey silts. These soil conditions are particularly suitable for accurate f_s profiling.

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