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Technical Paper

Characterisation of a high plasticity marine clay using a T-bar penetrometer

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Abstract

A series of laboratory-scale T-bar penetrometer tests have been conducted on a clay bed virgin consolidated from reconstituted high plasticity marine clay. This investigation was mainly concerned with the effects on the penetration resistance of rate of penetration and the presence of free water on the surface of the clay bed. The rate of penetration varied between 0.005mm/s and 50mm/s. The results showed that the nature of soil resistance was 'undrained' over the range of speeds studied, and the resistance showed a marked viscous rate effect. The virgin consolidated clay bed exhibited an increase in penetration resistance by up to 35% for a factor 10 increase in rate of penetration – much larger than values previously reported for kaolin. The presence of water on the surface of clay bed had a profound impact on penetration resistance, particularly on the remoulded strength obtained by taking the T-bar through successive penetration and extraction cycles. This was true even when the remoulding cycles were conducted without the T-bar breaking through the clay surface.

Keywords: T-bar, characterisation, marine clay, shear strength, undrained, rate effect

1. Introduction

A site investigation tool was required to characterise test clay beds intended for investigating the interaction response to longitudinal movement of partially embedded pipelines on clay seabeds. These clay beds were prepared by virgin consolidating reconstituted samples of natural high plasticity marine clay. An accurate estimate of the shear strength of these clay beds is vital for interpreting axial pipe-soil interaction response. A laboratory-scale T-bar penetrometer was proposed, as it is not only simple to construct and use but also apt for characterising soft sediments, and gives a direct and continuous measure of shear strength.

The present paper describes an experimental investigation undertaken to characterise the natural marine clay using a T-bar penetrometer. The main objective of this study was to examine the effect on the penetration resistance of: (a) the rate of T-bar penetration, and (b) the presence of free water on the surface of clay bed.

2. T-bar penetrometer testing

Stewart and Randolph (1991) developed a full flow T-bar penetrometer, especially for characterising soft clays in the centrifuge, and it is currently used for *in situ* testing of soft clay deposits offshore. However, another full flow penetrometer, the ball penetrometer, is increasingly becoming prevalent owing to its inherent merits over the T-bar. DeJong et al. (2011) and Low et al. (2010) reported a comprehensive study using full flow penetrometers (T-bar and ball), while Lunne et al. (2011) and DeJong et al. (2010) offered guidelines for full flow penetrometer testing, including equipment design, test procedure and data analysis.

A laboratory-scale T-bar penetrometer was proposed for the present study, as it is appropriate and was readily available for use.

2.1. Principles

The T-bar penetrometer continuously measures the resistance to penetration as it advances through a soft clay layer at a constant speed, creating a viscous flow of soil around the penetrometer.

The measured penetration resistance (q_m) should be corrected for unequal pore pressure and overburden pressure effects using the following simplified expression (Chung and Randolph, 2004):

$$q_{T\text{-}bar} = q_m - \left[\sigma_{v0} - u_0(1-\alpha)\right]\frac{A_s}{A_p} \qquad (1)$$

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where $q_{T\text{-}bar}$ is the net T-bar penetration resistance; q_m is the measured penetration resistance; σ_{v0} is the *in situ* total overburden stress; u_0 is the hydrostatic water pressure; α is the net area ratio (defined as the ratio of cross-sectional steel area at the connection to the T-bar to the projected area of connection shaft); A_s is the cross-sectional area of connection shaft; and A_p is the projected area of penetrometer in a plane normal to the shaft. From the net penetration resistance, the intact undrained shear strength (s_u) of the soil is estimated using the following expression:

$$s_u = q_{T\text{-}bar}/N_{T\text{-}bar} \quad (2)$$

where $N_{T\text{-}bar}$ is intact T-bar resistance factor.

In full flow penetrometers, the T-bar factor is less affected by soil rigidity and stress anisotropy because the soil flows around, rather than being displaced by, the advancing penetrometer, as in cone penetrometer tests. This allows for sound theoretical analysis and estimation of shear strength of soil.

Based on a plasticity solution for an infinite vertical cylinder moving laterally through a simple isotropic rigid perfectly plastic soil with a Tresca failure criterion, Randolph and Houlsby (1984) deduced $N_{T\text{-}bar}$ values in the range of 9–12 depending on the surface roughness of the T-bar. These $N_{T\text{-}bar}$ values hold good for a full flow-around mechanism, which is expected to be mobilised only after the T-bar has advanced to a depth of at least 3–4 T-bar diameters depending on its surface roughness.

Smaller $N_{T\text{-}bar}$ values therefore apply for shallower penetrations, where the mechanisms are different. White and Randolph (2007) have proposed an expression, based on the results of numerical analysis presented by Barbosa-Cruz and Randolph (2005), to capture the variation of N_b over a depth of penetration up to 4 T-bar diameters.

Real soils, however, exhibit anisotropy, rate dependency of shear strength and strain softening, all of which affect the T-bar factor. Further, the reference shear strength measured from element testing of high quality soil samples to calibrate penetrometer data also affect the T-bar factor (Randolph and Andersen, 2006; Randolph et al., 2007; Low et al., 2010; DeJong et al., 2011).

Full flow penetrometers, such as the T-bar, can also be used to measure the remoulded undrained shear strength (s_{ur}) of the soil (Watson et al., 2000). This is achieved by taking the T-bar through successive penetration and extraction cycles about the desired depth, remoulding the soil within the zone of influence of the T-bar. The remoulded undrained shear strength (s_{ur}) can be estimated using the following expression:

$$s_{ur} = q_{T\text{-}bar,r}/N_{T\text{-}bar,r} \quad (3)$$

where $q_{T\text{-}bar,r}$ is the T-bar penetration resistance in remoulded soil corrected for unequal pore pressure and overburden pressure, and $N_{T\text{-}bar,r}$ is the remoulded T-bar resistance factor. The $N_{T\text{-}bar,r}$ is shown to be different and higher than the intact T-bar resistance factor ($N_{T\text{-}bar}$), and it exhibits rate dependency (Randolph and Andersen, 2006; Randolph et al., 2007; Low et al., 2010).

The sensitivity (S_t) of the soil may then be estimated using the expression in Equation 4, provided the soil is being remoulded at constant water content during cyclic T-bar testing:

$$S_t = s_u/s_{ur} \quad (4)$$

2.2. Rate of penetration

Rate of penetration is one of the key parameters that govern the nature of soil response (undrained, partially drained or drained) around the T-bar and the resulting penetration resistance.

Two contrary effects come into play, depending on the rate of T-bar penetration (House et al., 2001; Lehane et al., 2009). The viscous effect occurs at higher penetration rates, where the penetration resistance increases with increasing rate of penetration, providing undrained conditions prevail in the soil around the T-bar. However, partial consolidation and strengthening of soil occurs at slower rates of penetration, where the penetration resistance increases with decreasing rate of penetration.

Fig 1 illustrates this effect of rate of penetration on the measured resistance of a T-bar (diameter 5mm) in normally consolidated kaolin clay (LL 61%; PI 34%; clay fraction 70%) in a centrifuge (Randolph and Hope, 2004).

The intact penetration resistance ($q_{T\text{-}bar}$) is normalised against the reference penetration resistance at v = 1mm/s. $q_{T\text{-}bar,ref}$ is plotted against the non-dimensional penetration rate, $V = vd/c_v$, where v is the rate of penetration; d is the diameter of T-bar; and c_v is the coefficient of consolidation.

From inspection of test data, for non-dimensional rates ($V > 20$) there seems to be a marginal increase in normalised resistance with speed attributable to viscous effects. However, the normalised penetration resistance increases with decreasing speed for $V < 10$ owing to increase in degree in consolidation with decrease in rate of penetration. House et al. (2001) reported viscous rate effects in kaolin for non-dimensional speeds ($V >$ 30–100).

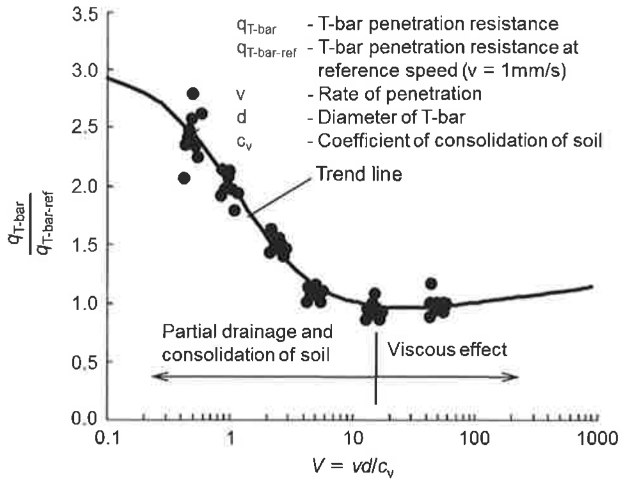


Fig 1: Effect of T-bar penetration rate on penetration resistance in kaolin (modified after Randolph and Hope (2004))

Most T-bar penetrometer tests concerning rate dependence of penetration resistance were conducted on normally consolidated kaolin, and little information is available for natural clays.

2.3. T-bar test setup

Fig 2 illustrates the T-bar penetrometer test setup. The laboratory-scale T-bar is made of brass and consists of a horizontal cylindrical bar 12mm in diameter and 110mm long. Two thin Teflon discs affixed at the ends of the bar help minimise the end friction, while the horizontal bar itself was sand blasted to make the surface rough.

The horizontal bar is fastened to the tip of a vertical cylindrical shaft 10mm in diameter. To ensure full flow conditions and proper estimate of soil strengths, a length-to-diameter ratio between 4 and 10 is recommended (DeJong et al., 2010; Lunne et al., 2011; Chung and Randolph, 2004). The length-to-diameter ratio of the T-bar used herein is about 9, while the ratio of projected area of bar normal to shaft-to-shaft cross-sectional area is about 16.

A push-pull type load cell with 400N capacity was used to measure the penetration and extraction resistance at the top end of the vertical shaft, and a draw wire potentiometer tracked the corresponding vertical displacement. The vertical carriage of a two-directional actuator generated constant speed cyclic displacement in the vertical direction. The actuator was mounted on a mobile steel frame, enabling to position the T-bar at the desired locations on the clay bed.

In the present T-bar setup, the penetration resistance was measured at the top of the vertical shaft (see Fig 2). Therefore, the measured resistance included vertical shaft friction in addition to bar resistance. However, the shaft friction was allowed during data analysis.

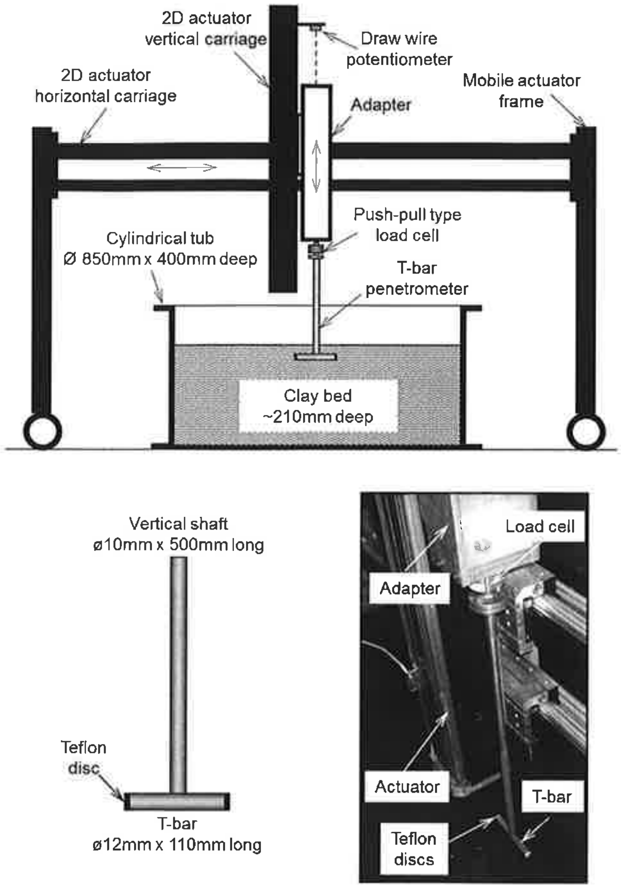


Fig 2: T-bar test setup

3. Properties of clay

The natural marine clay tested has a very high clay fraction (2μm) of 80% and also contains 7.2% organic matter. The mineralogical composition comprises kaolinite (50%), quartz (15%) and illite (10%), with smectite, chlorite, calcite, goethite and feldspar occupying the remaining 25%. The plastic and liquid limits are 80% and 175%, respectively. The *in situ* water content of about 200% in the top 1m corresponds to a bulk unit weight of ~12.7kN/m^3. The specific gravity of the soil solids is 2.73. The coefficient of consolidation of the reconstituted clay sample varies from 0.04 to 0.07m^2/year, as the one-dimensional normal consolidation pressure increases from 2.5 to 10.0kPa, and the corresponding permeability values are 7.4×10^{-10}m/s and 5.1×10^{-10}m/s.

4. Testing programme

The characterisation process involved two main stages: (a) preparation of virgin consolidated clay

Table 1: Test conditions and parameters

Test ID	Number of passes*	Rate of penetration (mm/s)	Soil surface condition
Test 1	20	5	Dry (or no free water)
Test 2	20	5	
Test 3	20	20	
Test 4	20	50	
Test 5	9	0.5	
Test 6	6	0.05	
Test 7	1	0.005	
Test 8	20	5	Submerged under water
Test 9	20	5	
Test 10	20	20	

* Each pass constitutes one penetration or extraction cycle

bed; and (b) T-bar penetrometer tests on virgin consolidated clay bed.

4.1. Preparation of test clay bed

A test clay bed was prepared in a cylindrical tub, 850mm in diameter and 400mm deep, by consolidating the reconstituted clay sample. The initial thickness of the clay sample was ~270mm and its moisture content was ~205%. To enable two-way drainage during consolidation, a layer of geotextile stiffened by geomembrane and covered by filter paper was provided at the top and bottom of the clay layer. A perforated loading platen was then placed on the drainage layer. Consolidation pressure was applied in stages over two days using dead weights. The maximum consolidation pressure at the end of day two was 6.05kPa, which was maintained for 60 days. The final thickness of clay bed was ~210mm.

4.2. T-bar penetrometer tests

Immediately after the loading platen was removed, a total of ten T-bar penetrometer tests (tests 1 to 10) were conducted on the virgin consolidated clay bed. Table 1 summarises the test conditions for each test.

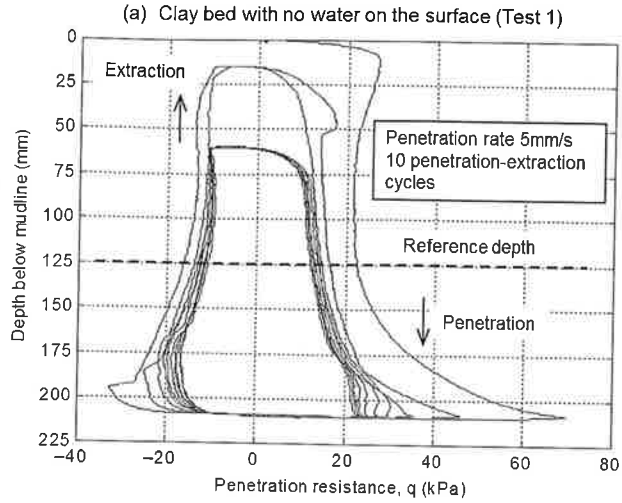
The rate of penetration was varied from 0.005 to 50mm/s (4 orders of magnitude). Each test generally constituted 20 passes (or 10 penetration-extraction cycles) except for a few tests (tests 5, 6 and 7) at slower rates. Further, in tests 1 to 7, no free water was available on the surface of the clay bed, but was kept moist so as to prevent drying of clay. However, the clay bed was submerged under water during tests 8 to 10.

5. Test results

5.1. Characteristic cyclic response

Figs 3a and 3b show the typical response of cyclic T-bar penetration tests on the virgin consolidated clay bed for dry and submerged conditions of the clay surface, respectively. The penetration resistance profiles of the first pass reveal that the soil layers near the drainage boundaries achieved a higher degree of consolidation compared to the middle layers. Although this indicated that the primary consolidation of the clay bed was only partially complete, this is not expected to affect the objectives of this study.

In order to capture the variation of penetration resistance with a number of passes, a reference depth was chosen in the clay bed, which was at about 125mm from the surface. The reference depth was remote from the drainage boundaries so that the effect of stress relaxation caused by swelling of clay would be minimal. This enables identical soil conditions at the reference depth over the entire range of T-bar tests, and is essential for evaluating the effect of variation of parameters under consideration.



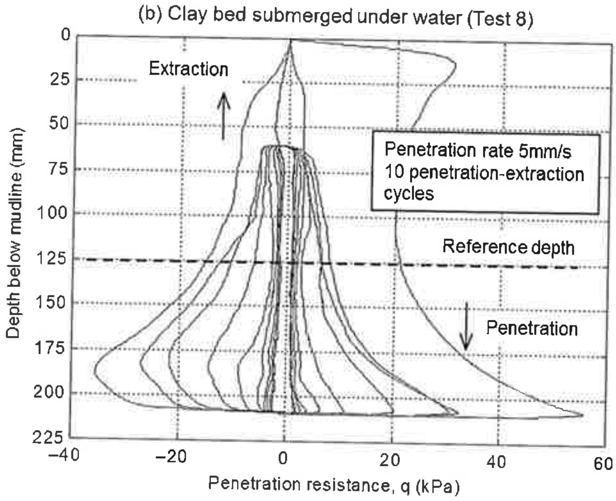


Fig 3: Typical T-bar penetration resistance profiles of virgin consolidated clay bed: (a) clay bed with no water on the surface (test 1); and (b) clay bed submerged under water (test 8)

Fig 4 compares the variation of penetration resistance at the reference depth with number of passes for tests 1 to 7, during which the surface of the clay bed was simply kept moist (no free water).

The penetration resistance increased with increasing rate of penetration, but decreased with number of passes regardless of rate of penetration. It reached a steady state after 15 passes (or 7 penetration-extraction cycles), indicating that the clay had been fully remoulded under the action of cyclic T-bar penetration and extraction.

This is consistent with the results of *in situ* T-bar tests reported by Chung and Randolph (2005), DeJong et al. (2005) and Yafrate and DeJong (2005). However, the number of T-bar cycles required to fully remould the soil is likely to be affected by the sensitivity of soil (Yafrate and DeJong, 2005). The sensitivity of the clay tested here might be about 2, as the steady-state remoulded resistance is roughly half of the corresponding resistance at the first pass (see Fig 4) and the clay is expected to be remoulded at constant water content. The sensitivity of the clay appears to be independent of the rate of penetration.

As for tests 5 and 6, it should be noted that the total number of passes was less than 15. However, the clay was considered adequately remoulded at the last pass as the degradation curve was almost stabilising (see Fig 4) and any further reduction in penetration resistance would be insignificant.

5.2. Effect of rate of penetration

The rate of penetration was varied between 0.005 and 50mm/s among tests 1 to 7. Fig 5 captures the effect of rate of penetration on both intact and remoulded resistances. The penetration resistance is normalised against the reference resistance measured at 5mm/s, while the rate of penetration

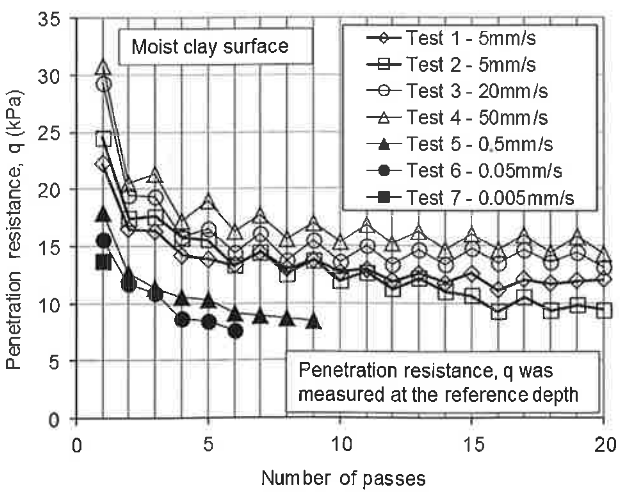


Fig 4: Variation of penetration resistance with cyclic T-bar penetration and extraction, and rate effect

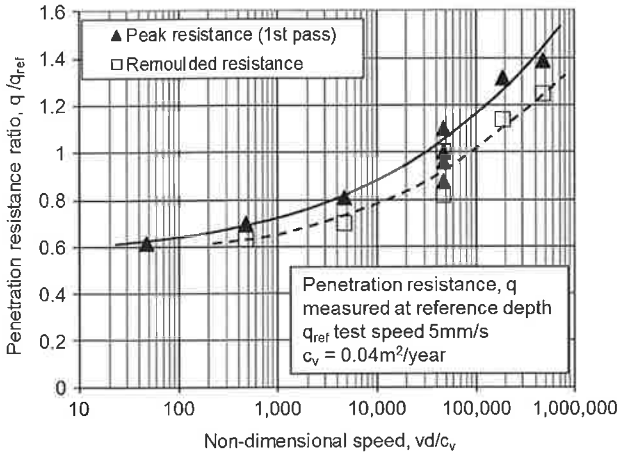


Fig 5: Variation of intact and remolded resistance with rate of penetration

is interpreted as non-dimensional speed, vd/c_v, where v = rate of penetration, d = diameter of T-bar and c_v = coefficient of consolidation of clay, which is taken to be equal to 0.04m^2/year. This corresponds to an effective stress during precompression of about 3.0kPa at the reference depth.

For the range of penetration rates (the equivalent non-dimensional speed range, $50 < vd/c_v < 50,000$) considered here, undrained conditions were likely to dominate. This is evident from the results (see Fig 5) that only the viscous effect is observed. This is also consistent with the threshold non-dimensional speed, $vd/c_v \approx 20$, reported by House et al. (2001) for the onset of undrained conditions in T-bar testing. This response is attributable to the consolidation characteristics of the clay ($c_v \approx$ 0.04m^2/year), which is about 100 times slower than the c_v value of kaolin (commonly used in geotechnical laboratories for studies involving clays). In order to be able to see any partially drained condition in this testing, the penetration rate would have to be smaller again by two orders of magnitude. At 0.00005mm/s, it would take up to a month to achieve a single penetration pass of 130mm.

The penetration resistance of both intact and remoulded soil increases with increasing rate of penetration. For example, for intact soil, it increases at a rate up to about 35% per log cycle of non-dimensional speed (vd/c_v) greater than 5,000. This is considerably higher than the typical values reported in the literature for viscous rate effect: 5–20% per log cycle of increase in strain rate (Rattley et al., 2005; Einav and Randolph, 2006).

Although the effect of rate of penetration on the remoulded resistance is comparable to that of the intact soil, there is a lateral shift in the remoulded resistance curve by a factor of about four towards the higher side of vd/c_v (see Fig 5). This indicates that the c_v of the remoulded soil may be smaller by a factor of four compared to that of intact soil. This is perhaps owing to the generation of positive pore pressure as the soil remoulds during cyclic T-bar testing, and hence a reduction in effective stress in the soil. The c_v is likely to be smaller under smaller effective stresses.

It is difficult to define a standard penetration rate for the full flow penetrometers, like the T-bar, so that the strength of soil obtained from them is comparable to that of vane shear test, direct shear test, etc. This is because the mechanisms involved in these testing methods are different and therefore different standard rates are specified. Moreover, the nature of soil response (drained, partially drained or undrained) and the measured soil strength are affected by soil properties or conditions such as coefficient of consolidation, sensitivity and stress history, in addition to the displacement or shearing rates.

5.3. Effect of free water on the surface of clay bed

Two sets of T-bar tests, tests 1 to 3 and tests 8 to 10, were intended to study the effect of availability of free water on the surface of clay bed on the penetration resistance. As shown in Table 1, the test conditions of these two sets of tests are comparable, except where the clay bed was completely submerged under water during tests 8 to 10. Furthermore, the effect of rate of penetration was also addressed; tests 3 and test 8 were conducted at a faster rate (20mm/s), while the other tests were conducted at 5mm/s.

Fig 6 compares the penetration resistance at the reference depth for those six tests (tests 1 to 3 and tests 8 to 10). The availability of free water to the clay during cyclic T-bar testing has a significant impact on the penetration resistance, although the penetration-extraction cycle was performed in the bottom 150mm of the 210mm-thick test bed.

The reduction in penetration resistance of the clay bed submerged under water was only 2–3kPa during the first two passes. Thenceforth it accelerated very fast and reached a negligible value, i.e. 1–3kPa (tests 8 to 10), whereas the corresponding penetration resistance in the test bed with no water at the surface was 10–13kPa at the end of pass 20 (tests 1 to 3). A marginal rate effect was also seen in both cases.

This drastic drop in penetration resistance of the virgin consolidated clay bed submerged under water is because of the mixing of clay with water that was drawn into the soil on first penetration, and subsequently remains available to being remoulded by the passing T-bar. The water content of the remoulded clay increased with an increase in the number of passes. This resulted in a very small penetration resistance within 15 passes. For tests 1 to 3, on the other hand, the clay had no access to water, and it remoulded almost at the same water content by the passing T-bar.

The undrained remoulded strength (s_{ur}) in Equation 2 is now seen to be highly sensitive to the availability of water to the remoulding soil. Cyclic T-bar tests close to the seabed surface are highly vulnerable even when the penetrometer extraction is restricted to below the clay surface. Therefore, the sensitivity values obtained from such full flow penetrometer testing has to be used with great caution, and certainly cannot be relied on in the top 0.5m of the profile.

The undrained shear strength measured during the first pass of the T-bar also seemed to be affected by the presence of water, but it is hard to make any conclusive remarks based on the spare data available from the present study and the marginal effect.

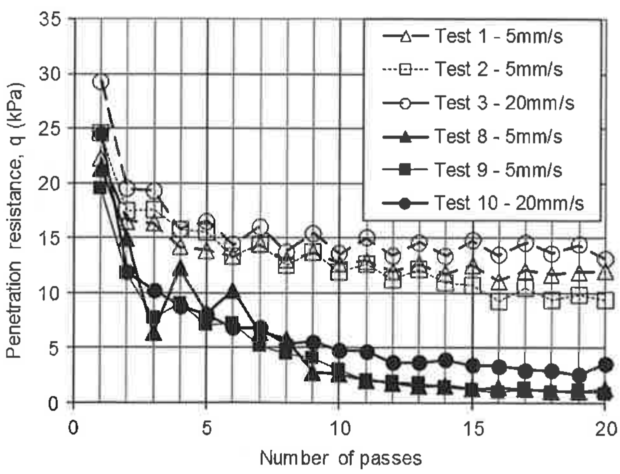


Fig 6: Effect of free water on the surface of clay bed on the penetration resistance at reference depth

6. Summary

A high plasticity natural marine clay bed – virgin consolidated from reconstituted slurry – has been characterised using a laboratory-scale T-bar penetrometer. The main objective was to determine the effect of rate of penetration and presence of free water on the surface of clay bed on the penetration resistance. The salient outcomes of this characterisation study are as follows:

- The soil response was 'undrained' over the speed range 0.005–50.0mm/s ($50 < vd/c_v < 50{,}000$) studied, and the resistance showed a marked viscous rate effect.
- The clay exhibited up to 35% increase in penetration resistance for a factor 10 increase in rate of penetration – much larger than the typical

values of 5–20% reported in the literature for viscous rate effect.

- The penetration resistance degraded with the number of T-bar penetration-extraction cycles and reached a steady state after seven T-bar cycles as the soil was fully remoulded. The sensitivity (S_t) of the clay is about 2 and is independent of rate of penetration.
- Presence of free water on the surface of clay bed had a profound impact on the penetration resistance, particularly on the remoulded strength. This was true even when the remoulding cycles were restricted to below the clay surface.
- When submerged under water, the virgin consolidated clay bed exhibited a negligible remoulded resistance after seven T-bar cycles.

7. Conclusions

The areas of the seabed where deepwater hydrocarbon field development has been active are predominantly made of soft and high plasticity marine clays, which typically have very low coefficient of consolidation. Due consideration must therefore be given to the rate of penetration and consolidation characteristics of soil while interpreting T-bar data.

The soil parameters of the upper 0.5m layers of the seabed are critical for the design of pipeline or flowlines. These uppers layers are most likely to entrain sea water and get mixed up during cyclic T-bar testing. This would result in quick degradation of penetration resistance with T-bar cycles and might reduce to a negligible value. The interpretation of T-bar tests in terms of soil sensitivity at constant water content needs to be reconsidered if any water entrainment is envisaged.

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