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Strain Rate Characterization of Soft Clay using T-bar

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Abstract. In recent years, reliance on offshore resources has increased into many folds. Due to the significant technological advancement, policymakers throughout the globe now trust the modern offshore structures built for various proposes like harnessing wind & wave energy, mining, military uses, etc. In offshore conditions, foundation requirements considerably change with the water depth. As in the deepwater floating structures are preferred, and usually anchor systems are provided at the seabed to support the floating structures. Nowadays, for deepwater, dynamically installed anchors are gaining popularity. For the design of a dynamically installed anchor, it is essential to know the strain rate dependence behavior of soils. Usually, failure deviator stress increases with the increased strain rate. It is often found that the deepwater sediments usually are consolidated clay. The shear strength of these clay sediments is low and often less than 10kPa. Conventional tube sampling and subsequent laboratory tests on such low strength soil are not practically possible. Therefore, field test is the only alternative that can use to know the strength profile of deep-sea soil strata. T-bar has been widely used to determine the strength profile in offshore conditions. It is more effective in the case of soft clay and silt. There has been extensive literature available on the use and interpretation of T-bar test results. However, the effectiveness of the T-bar to characterize the strain rate effect is not yet fully understood. In this research, a database has created on the T-bar test conducted at the various rate of penetration. From the database, it was observed that the penetration resistance increases with the increase in the rate of penetration.

Keywords: T-Bar, Full flow penetrometer, Dynamically installed anchors, Strain rate of different soil.

1 Introduction

Construction activity in offshore has increased into many folds. The soil strength characteristics of the seabed must be known in order to finalize the type of foundation and structural design of the foundation. It is a fact that the foundation requirements change with the change in water depth. At deepwater, usually, a floating platform is more economically suitable. These floating structures need a mooring system, which can be provided by the deepwater anchoring system. To design a deepwater anchor strength profile of soil strata needs to be determined. Geotechnical investigation at deep sea is always expensive and collection of a good quality soil sample cannot be guaranteed. A field test at seabed may consider as an alternative. Nowadays, field tests like CPT (Cone penetration test) and T_{bar} or Ball penetrometer are often used in offshore. Both the field tests can be used to make continuous soil profiling with excellent soil strength characterization.

Torpedo anchor is one such deep water anchor system. These are rocket-shaped, cost-saving and effective anchoring system for the offshore floating structures in deep waters. One of the most critical elements in the design of the torpedo anchor is the characterization of the strength properties of soil in terms of its strain rate (rate of shearing) effect. Thus, it is very pertinent that during the designing of torpedo anchor, knowledge regarding the strain rate behavior of the soil should be attained beforehand. T_{bar} has some advantages compared to the CPT to study the strain rate effect in the field. Unlike CPT, T_{bar} can push into the soil strata at a very slow rate to a very high rate of penetration. Initially, T_{bar} was used by Stewart and Randolph in centrifuges for soil profiling of soft clay. T_{bar} found rising popularity with time. The penetration resistance in a T_{bar} is not dependent upon the rigidity index (I_r). Apart from this, in soft soil T_{bar} has shown better accuracy due to the increased projected area of the penetrometer. The second is the minimal correction for overburden stress (Jannuzzi et al., 2017). In recent times, T-Bar has become a vital tool for offshore site investigations (although dimensions and the test procedures of the T_{bar} are still in the way of being standardized). In this paper effectiveness of T_{bar} test to capture the strain rate effect of soil will be studied. Base on the published literature, a database will be created on various rate control T_{bar} test. The database will be further analyzed in terms of change in bearing factor with the change in the penetration rate ofT_{bar}.

2 Historical Background

T_{bar} first developed at the University of Western Australia in 1991 by Stewart & Randolph. T_{bar} penetrometer was initially used to estimate the undrained shear strengths of clay samples tested in a centrifuge. This novel innovation harnessed the combination of the advantages of the Cone Penetrometer Tests (CPT or CPTU) which depicted a continuous 'strength-profile' and that of the Vane Shear Test, which indicated 'an exact' or 'direct measure' of the shear strength. Furthermore, T-Bars also allowed the soil to flow around the T_{bar} cylinder, thus reducing the corrections for overburden stress, as opposed to the conventional Cone Penetrometer Tests (CPT) [1,2,3] completely.

It was in the year 1994, in Burswood, Australia, the T_{bars} were first introduced in the field. It then comprised a long aluminum bar 50 mm in diameter and 200 mm in length, attached at right angles to a shaft with the penetration resistance measured just behind the cylinder with a rate of penetration of 20 mm/s. Later on, in the year 1997, T-Bar Penetrometer Tests were conducted in Australian waters for assessing the profile of undrained shear strength with depth, with a slight modification in its dimensions. Fig.1 has shown a typical T_{bar}. The bar now is a 250 mm length and a 40 mm diameter, thus increasing the projected area by ten times than that of the shaft of a standard cone penetrometer. It also consisted of a built-in device that incorporated two pore pressure transducers (within the cylindrical bar) and its own load cell

(Randolph et al, 1998). Nine months later, in the year 1999, this device was again used in Australian waters by Hefer & Neubecker[4,5,6,7].

In recent times, T-Bar Penetrometer tests have become an indispensable method in offshore site investigations especially in soft clay. Although, the exact dimensions of the device to be used and proper test procedures are still in the way of being standardized.

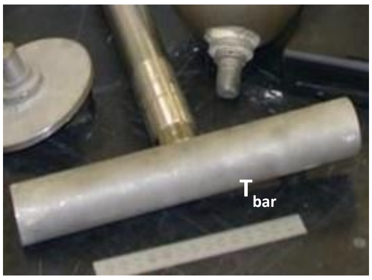


Fig.1. Photograph of a T_{bar} (Yafrate et al. 2007)

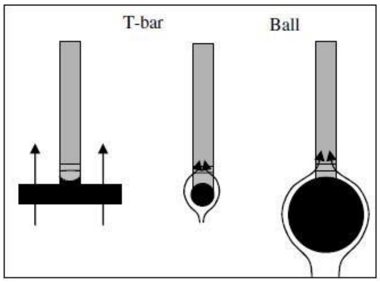


Fig. 2. Graphical representation off Full Flow mechanism of T_{bar} penetration (Yafrate et al. 2007)

3 Mechanism of T-Bar

3.1 Full-flow penetrometer

The utilization of full-flow penetrometer to estimate the soil sensitivity and the undrained and remolded shear strength of the soft sediments (like silt and clay) have increased manifold in industries and by researchers over the past decade. One of the many reasons that have led to its increased significance is the number of advantages that it holds over the common piezocone CPTu (cone penetrometer test) and FVT (field vane shear test).

Firstly with the larger penetrometer projected area (around 10000 mm^2), its accuracy in soft soils has enhanced to quite a remarkable extent. Secondly, the correction for overburden stress has been brought to a minimum (which is almost the same as above and below the full-flow penetrometer). Thirdly, substantial theoretical analysis of the rate of penetration and the estimation of shear strength was possible due to the depiction of a well-defined failure mechanism (plane strain flow - T-Bar and axisymmetric flow - ball and circular plate). Lastly and most importantly, their potential of utilizing cyclic degradation testing to estimate the remolded strength characteristics have accentuated its utilization on another level (the later being possible because, in a full-flow penetrometer, the soil tends to occupy almost the same volume).

The only drawback that one can point out is the fact that full-flow penetrometers can be used in only soft sediments at the depths where the overburden stress sufficient enough for the full-flow mechanism to be established.

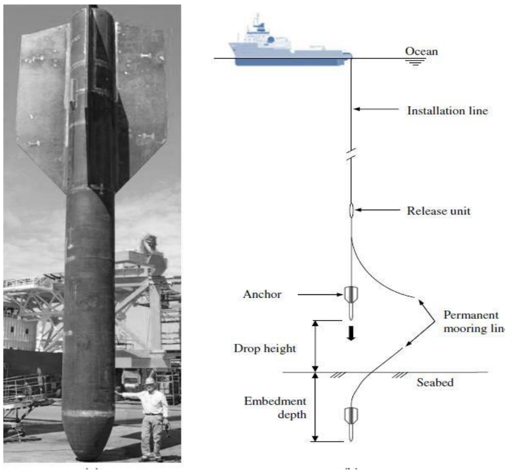


Fig.3. Dynamically installed anchors (a) deep penetrating anchor (b) installation procedure (O'Loughlin etal.)

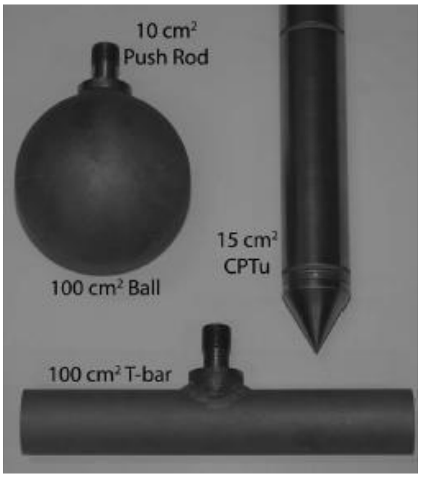


Fig.4. Penetrometers - Cone, Ball and T-Bar (DeJong et al.2011)

3.2 Transfer of soil parameter by T_{bar}

The most fundamental way in which the T-bar test is evaluated comprises of the conversion of penetration resistance (q_{bar}), into undrained soil shear strength (S_u), using T-bar bearing factor (N_F or N_c):

$$N_F \ or \ N_c = \frac{q_{bar}}{S_u} \qquad (1)$$

The penetration resistance (q_{bar}) can be measured during T_{bar} penetration. The shear strength of that soil can be obtained using equation (1) if the bearing factor is (N_F or

N_c). The bearing factor is usually obtained by calibrating the T_{bar} with a known shear strength of a soil. The N_F and N_c represent bearing factors determine using shear strength obtained from the field vane shear test and consolidated undrained test respectively.

Using the Plasticity limit analysis, Gaudin et al. [19] stated that the N_F values range from 9.14 (fully smooth interface) to 11.94 (fully rough interface and rigid-plastic soil) (based on observations by Randolph and Houlsby, 1984; Martin and Randolph, 2006). The T_{bar} that are used in the centrifuge and the field were neither fully smooth nor rough, both Stewart & Randolph observed value of N_F to be 10.5. The values so formed were a result after the experimental calibration by making use of a range of material types, stress histories and stress levels. Recent studies have helped in further understanding of the selection of N_F, thus acknowledging the variation in the operative undrained strength in different types of in-situ or laboratory tests, as observed by Lunne et al., 2005 and the impact of softening and rate effects as observed by Einav and Randolph, 2005 after withdrawing the assumption of an ideal rigid-plastic soil. The two principal mechanisms that have been observed to affect the near-surface penetration resistance of a T_{bar} are listed as follows:

1. Variability in resistance from soil strength when the failure mechanism changes from surface drag to deep flow round.
2. Variability in resistance from soil buoyancy, when failure mechanism comprises of different degrees of soil drag and thus affecting the work done against the soil's self-weight at different depths.

4 Dynamically Installed Anchors

Fig. 4 shown a photograph of dynamically installed anchors, which are torpedo or rocket-shaped anchoring system for the offshore floating structures in deep waters. As opposed to the conventional deepwater anchoring systems, the speed and ease of installing these anchors (even in deep waters), highlights their extensive utilization and acceptance in the geotechnical sphere in the present times as they have proved to be more effective and cost-saving. They are installed by just dropping them off from a certain height above the seafloor right into the ocean so that they can self-bury themselves in the seabeds with the help of the generated kinetic energy during the free-fall along with its self-weight (Richardson, 2008). Success in accurately forecasting the free fall, strain rate effect and the corresponding soil strength recovery after the anchor's installation governs the performance of these dynamically installed anchors.

5 Database

A database is prepared to study the T_{bar} behavior at various rates of penetration. The data was collected from four literatures; Nanda et al. (2017), Yafrate et al. (2007), DeJong et al. (2011) and Lunne et al. (2011). The database is shown in Table-1, which summaries the change in bearing factor with T_{bar} penetration rate. In Table-1 N_F and N_c represent bearing factor in terms of Field Vane Shear test and Consolidated Undrained Triaxial test respectively. Both the bearing factor was determined using equation (1). The shear strength in equation(1) remains constant for a given soil.

Table1. Bearing Factors

Author	Soil type	Penetration rate mm/sec	N_F value through FVT	N_c value through CAUC
Nanda et al. (2017)	Kaoline Clay	1	12.54	-
		10	13.22	-
		100	14.42	-
		600	15.53	-
Yafrate et al. (2007)	Silty clay	2	7.5	6
		20	7.25	5.8
	Silty clay	2	7.5	6.8
		20	7	6.3
	Silty clay	3	6.85	8
		20	7.1	8.4
	Clay Clay	3	5.1	8.8
		20	6.4	11
	Soft clay	2	10.4	5.2
		20	12.7	6.3
		200	13.8	7
	Soft clay	2	10.2	8
		20	11.1	8.6
		200	13.7	10.6
	Soft clay	0.2	9	9.5
		0.7	9.4	10
		2	10.1	10.6
		8	11.25	10.7
		20	11.5	10.9
	Soft clay	0.2	10.3	6.7
		0.7	10.9	7.1
		2	11.25	7.3
		8	11.6	7.5
		20	12.14	8

	Clay	20	9.1	8.8
DeJong et al. (2011)	rconsolidation clay	20	13.3	12
	Sensitive clay	20	5.7	6.8
	Soft clay	20	10.0	8.2
Lunne et al. (2011)	Soft clay	20	11.9	

[F]: FVT(Field vane test), [C]:CAUC (Consolidate undrained triaxial test)

Nanda et al., (2017) [21] performed series experiments to determine the effect of strain rate on undrained shear strength of kaolin clay. A T-bar made of aluminum was used to penetrate a 65 cm deep clay bed at different penetration rates. The shear strength was varied from 0 kPa to 3.4 kPa along with the depth. The T-bar was penetrated at 1 mm/s, 10 mm/s, 100 mm/s and 600 mm/s and the corresponding $N_F$values observed at the respective penetration rates were 12.35, 13.2, 14.6 and 15.5. An increase of T-bar resistance by 9% for each 10 times increase in the rate of penetration was observed.

Yafrate et al. (2007) reported of field studies of four sites. They have used both T-bar as well as a ball penetrometer in their study. In these four sites, the soil profile is varied between silty clay to soft clay. The value of soil shear strength was determined by FVT and CPCU. The T-bar penetration was made at the penetration rate in the range of 02.mm/sec to100mm/sec.

DeJong et al., (2011) [4] evaluated the undrained shear strength at different sites of soft to medium stiff clay at a constant penetration rate of 20 mm/s. A T-bar of diameter 40 mm and 250 mm long was used. Field vane test (FVT) and consolidated undrained triaxial compression test (CAUC) were conducted in the same sites. It was observed that the soil strata of the site consist of highly plastic and low overconsolidated soil. The shear strength of the soil is about 18-20 kPa and the observed bearing factor obtained for FVT and CPCU was 13.3 and 12.0 respectively. Similarly, the shear strength at the site having soft clay varied from 15-19 kPa with bearing factor for FVT and CPCU is 10 and 8.2respectively.

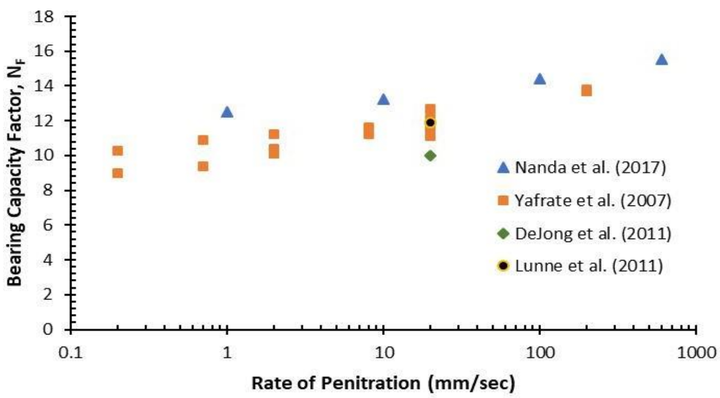
Lunne et al., (2005) [13] experimented with the deposit of low OCR clay in order to account the different parameters. The observed shear strength varied from 1.5 kPa to 4.0 kPa with depth. The bearing factor was recorded as11.9.

6 Discussion

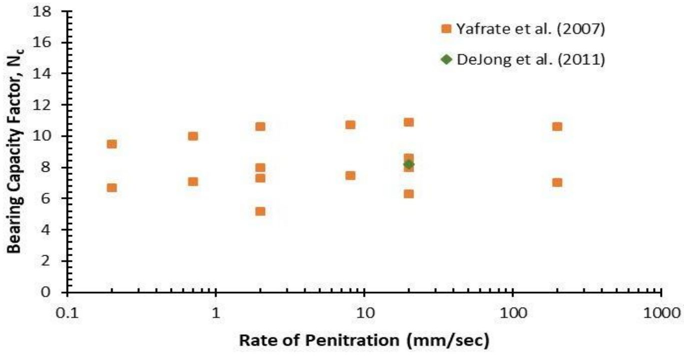
Fig. 5(a) shown change in bearing factor (N_F) with the rate of penetration for soft clay. The rate of penetration is shown in the x-axis, which is in the logarithmic scale. From Fig. 5(a) it can be observed that the N_F increases with the rate of penetration. The value of N_F increased from 10.5 at a slow rate of penetration to 15 at a penetration rate of 600mm/sec. Every tenfold increase in the rate of penetration, N_F value increases by about 10 to 12 percentage in its previous N_F value. Fig.2 (b) represents the change in bearing factor (N_c) with the rate of penetration for soft clay. Like N_F, N_c value also increases with the rate of penetration. N_c value is relatively more scatter than that of N_F with the strain rate. This signified the uncertainty with mapping the T-bar resistance with the laboratory test like a consolidated undrained triaxial test.

From Table 1, the value of N_F is considerably higher than the N_c value. The Nc value can be in the range of 95 to 70% of N_F. The value of N_F is around 7 in the case of silty clay soils, which indicates a significant reduction in comparison to soft clay. For the peak resistance the recommended value of bearing factor at a penetration rate of 20mm/sec is 10.5 .In the case of remolded soil, this may be in the range of 11 to 12.5 (Randolph and Susan 2011).The present data analysis suggests that at a penetration rate of 20 mm/sec, the bearing factor is in the range of 10.5 to 12. For silty clay soil, the bearing factor is around seven which is much less than the recommended value of 10.5. Thus, it may conclude that the recommended bearing factor is not suitable for silty clay soils. Furthermore, the recommended bearing factor is more for FVT than that of CPCU.

It would be more economical to perform T-bar at a high rate of penetration. However, a higher penetration rate will produce a strain rate effect to the T-bar resistance. The strain rate effect can be negated by using an appropriate bearing factor. From Table 1 & Fig. 5 it may be concluded that T-bar penetration resistance is sensitive to the rate of penetration. From Fig. 5(a), the N_F value at a high rate of penetration is 14.5 and 15.5 at 100 mm/sec and 600mm/sec rate of penetration respectively. Fig.5 indicates an almost linear variation of penetration resistance with the rate of penetration. Similar behavior is reported in the soil element tests where shear strength was increased with the increase in the rate of shearing. For the design of the torpedo anchor, it is essential to know the change in shear strength with the rate of shearing (strain rate). Equation (1) can be rearranged to determine the change in shear strength with the penetration rate.



(a)



(b)

Fig. 5. Variation if N_F and N_c for soft clay (a) Variation of Bearing Factor (N_F) with rate of penetration, (b) Variation of Bearing factor (N_C) with rate of penetration

$$S_u = \frac{q_{bar}}{N_F} \qquad (2)$$

In equation (2) let's keep N_F remain constant and its value should be in the range of 10.5 to 12. In order to ascertain the change in shear strength with the shearing rate, it is essential to know the change of q_{bar} at the various rate of penetration. To get q_{bar} at a different rate of penetration, it will require to conduct multiple T-bar tests at the site. However, this can be avoided by conducting a Variable penetration rate test. In the Variable penetration test, T_{bar} will be pushed in the soil at increasing or decreasing rate of penetration in the same soil layer. This gives relationship between q_{bar} and strain rate, and which can be used later in Eq. (2) to determine the strain rate effect on the shear strength of the soil strata.

7 Conclusions

The following conclusions may be drawn from this research

1. The bearing factor of T-bar penetrating in soft clay soil is in the range of 10.5 to12. The bearing factor decreases with the increase in soil shear strength.
2. T-bar resistance increases with the penetration rate and showing a similar trend usually observed in the soil element test, where shear strength increases with the increase in the rate of shearing.
3. A variable-rate penetration T-bar test may perform to determine the change in the shear strength of clay with the rate of shearing.

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