The influence of fins on the capacity of the Torpedo Base

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Abstract. The Torpedo Base is a cost-effective foundation system used by Petrobras since 2004 for offshore well conductor casings in very soft Brazilian marine clays. Uncertainties remain regarding the contribution of fins to bearing capacity and the mechanisms of controlling soil–structure interaction. A research and development project is under elaboration aiming at optimizing the design by increasing capacity and improving overall reliability. The project features both numerical and experimental studies. In the last case, three large-scale BT-1000 torpedo base models (1:5, 1:10, and 1:20) were manufactured to replicate the geometric characteristics and operational behavior of the full-scale system. The models were tested at the Sarapuí II soft clay test site. A probe was also instrumented with total stress cells to investigate the role of the fins on the capacity of the torpedo base. Both numerical and experimental studies have indicated that skin friction cannot be calculated based on the total surface of the fins.

1 Introduction

Petrobras has been using Torpedo Bases as a well conductor since 2004 [1]. Initially developed as a prototype for the Albacora Field, this technology is now widely used in the Campos and Espírito Santo Basins in Brazil. More than one hundred wells in these regions were built using almost the same prototype tested initially (with slight modifications). Building on the experience gained from this first model, a new generation of Torpedo Bases has been developed to meet evolving operational requirements and incorporate technological advancements**.**

The development of the BT-1000 Torpedo Base model (Fig. 1), featuring larger dimensions, began in 2013 and was intended for application in the Brazilian pre-salt area, in fields characterized by very soft clay profiles. This model was engineered to be integrated with long-extension surface casings (1000 m × 22" OD), which represented a significant challenge due to the high loads involved (~2900 kN) that the base needed to withstand.

Only one well used this design due to low confidence at the time in achieving full cement bonding between the conductor and surface casings. Today, improved cementing techniques ensure reliable integration and meet safety requirements.

The BT-1000 model consists in a 550 kN steel pile with a 26-meter-long, 36-inch-diameter tubular casing equipped with eight equally spaced fins. Four of these fins are wider (~950 mm) and are designated as primary fins, while the remaining four are referred to as secondary fins. The assembly includes a top-mounted box, known as the geomechanical brake, which prevents the top of the torpedo base from sinking into the seabed after being released from a few meters above. Inside the casing, there is a retrievable cylindrical ballast (243 kN) that functions as a hammer to complete penetration when the target depth is not achieved by free fall.

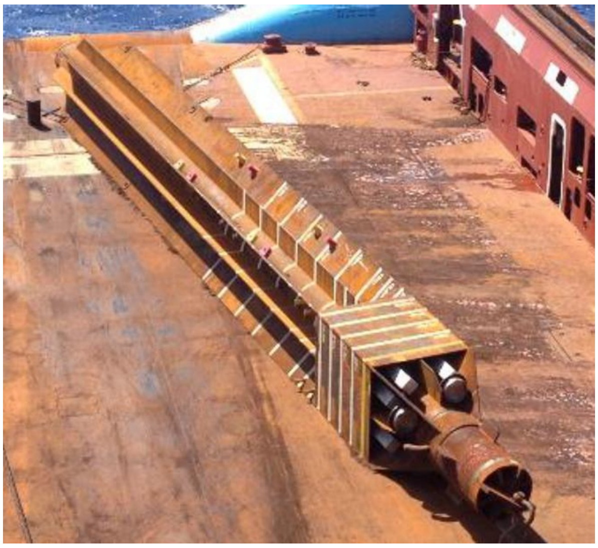

Fig. 1. BT-1000 on an AHTS vessel deck in offshore Brazil [2].

2 Soil conditions

Marine clays at the pre-salt region are generally encountered in very similar conditions to those described by Lunne et al. [3]. Several CPTu data

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collected in the region shows a normally consolidated soft clay with an increasing undrained shear strength along the depth that varies between 1.4 to 2.5 kPa/m. Thin marine surface crusts with higher apparent undrained shear strength may occur near the seafloor. As described by Ochi [4], these crusts are iron-rich or biologically formed hard layers, which significantly increase surface soil resistance, influencing the geotechnical parameters at that part.

To simulate these soft clays in experimental studies, an onshore test site is used. The Sarapuí II test site is in the Rio de Janeiro Metropolitan Region, close to Guanabara Bay. Several studies have already been carried out at this test site [5-10]. The very soft, high-plasticity soil in the test site area is a Holocene clay, deposited between 2000 and 8000 years before present (YBP) [8]. The main properties of the deposit can be seen in Fig. 2 and Fig. 3 [7]. The Sarapuí II clay has similar geotechnical properties to Brazilian pre-salt offshore clays, as verified by several laboratory and in situ tests, making Sarapuí II an international reference test site for studies on dynamic installation and performance of conductors and torpedo foundations in marine soft sediments.

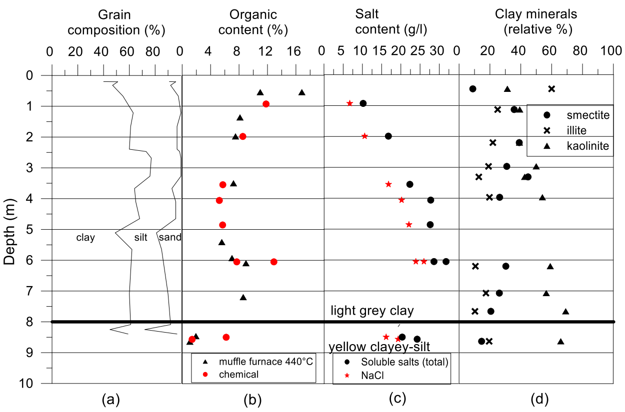

Fig. 2. (a) Grain size distribution; (b) organic content; (c) Total salt content and NaCl content; (d) relative percentage of clay minerals versus depth.

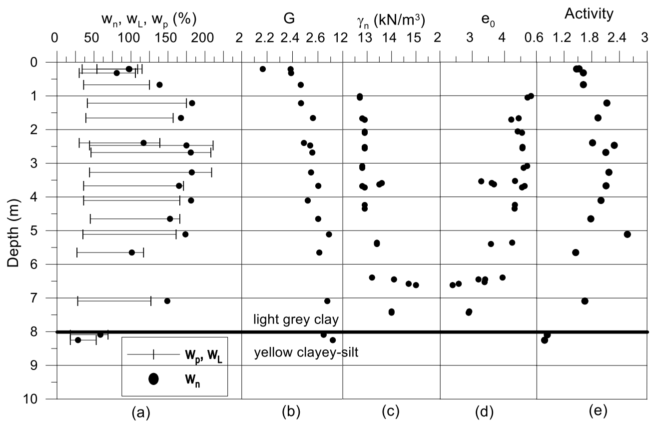

Fig. 3. (a)Liquid limit, plastic limit and natural water content; (b) specific gravity; (c) total unit weight; (d) initial void ratio; (e) activity versus depth.

3 The role of fins

Fins are critical components for ensuring the stability and bearing capacity of torpedo piles and torpedo bases, thereby affecting the performance and reliability of these foundations in offshore applications.

Silva [11] has shown, based on CFD (Computational Fluid Dynamics) simulations, that fins are crucial for the directional stability of torpedo anchors, directly influencing their trajectory, orientation, and performance during launch and penetration. For torpedo bases, stability is not yet a concern since field operations already reports excellent performance on this matter.

In terms of bearing capacity, fins are in place to increase the stiffness of the tubular casing and to increase the area in contact with the soil. Sousa et al. [12, 2] discuss the bearing capacity calculations for piles equipped with this type of components.

On the other hand, for driven piles in soft clays, the standard practice requires the bearing capacity (Q_s) to be calculated using the α-method, in accordance with API RP 2GEO [13]. In its most simplified form, this analytical method accounts for soil–pile adhesion coefficient (α), the undrained shear strength of the soil (S_u) and lateral area of the pile (A_s) as follows:

$$Q_s=\sum(\alpha \cdot S_u \cdot A_s) \quad (1)$$

An implicit assumption of Equation (1) is that soil failure occurs at the pile-soil interface. The same equation may suggest that adding more fins would naturally increase the shaft resistance by increasing the lateral area.

Nevertheless, Sousa et al. [2] show, using a three-dimensional finite element model, that "the use of more than four fins welded to the shaft of the conductor casing modifies the shear zone along the base but does not contribute to a significant increase in the axial holding capacity". Therefore, increasing the lateral area does not necessarily lead to a proportional increase in capacity. The actual impact of adding more fins to increase bearing capacity may require detailed investigation.

4 Numerical analysis

Sousa et al. [2] presented two complementary models to evaluate the bearing capacity of the BT-1000 embedded in soft marine clays under undrained conditions.

The first consists of a three-dimensional finite element model (FEM) in which the soil was represented using a perfect elasto-plastic constitutive formulation for normally consolidated clays (Drucker-Prager), with fully coupled soil–structure interaction along the shaft and fin surfaces, enabling detailed assessment of stress redistribution, plastic zone development, and global failure mechanisms. The 3D model is schematically presented in Fig. 4.

The second is a simplified analytical model based on DNV-GL cavity expansion theory that also takes time-dependent consolidation (setup effect) which

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dominate the long-term behavior of torpedo bases in soft clay.

Sousa et al. [2] further showed that the axial capacity of torpedo bases is governed by interface shear resistance, enabling the reliable use of simplified elasto-plastic model when soil–structure contact is properly modeled. The proposed closed-form formulation has been used as a practical tool for rapid estimation of ultimate capacity and preliminary parametric assessments.

Although not yet considered in the present analysis, previous studies have shown that different modeling approaches can lead to significantly different responses under vertical or lateral loading conditions [14]. Moreover, soil–structure interaction will be affected by several other soil-related factors, including rate effects, strain softening, pore fluid chemistry (e.g., salt solutions), and stress state, all of which influence the interface response, as highlighted by e.g., [15-19].

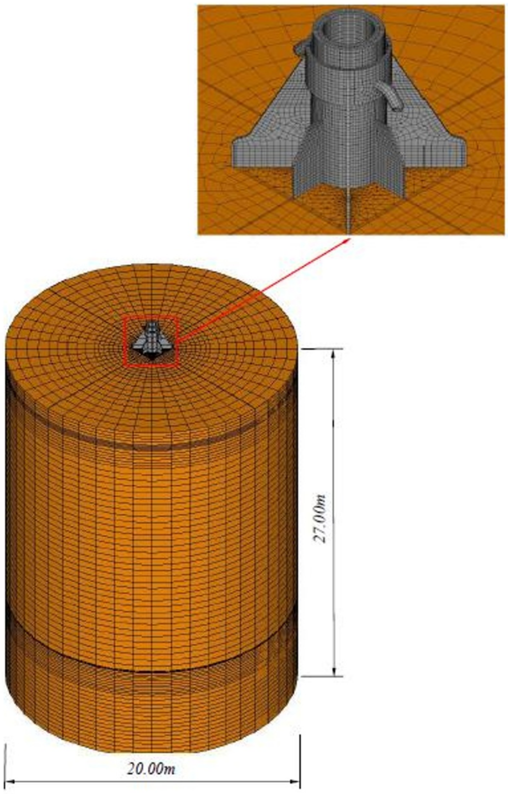


Fig. 4. BT-1000 FE model [2].

In the study herein presented, the axial load response of the BT-1000 configuration originally presented by [2] was reassessed considering geometric modifications involving (i) removal of secondary fins and (ii) increases in fin width and thickness, as proposed in Table 1. The previously developed three-dimensional FE model, validated against the analytical formulation, was adopted without modification for soil constitutive behavior, boundary conditions, mesh refinement strategy, material parameters, and loading procedure. This approach enables a direct and consistent evaluation of the structural influence of geometric refinements on the axial capacity.

Table 1. Modifications in the BT-1000.

Modif.	Characteristics
1	Same geometry. Secondary fins eliminated. 13% reduction in self-weight.
2	Same geometry. Secondary fins eliminated. Primary fins 33% wider and 56% thicker. 13% increase in self-weight.
3	Same geometry. Secondary fins eliminated. Primary fins 42% wider and 56% thicker. 16% increase in self-weight.

Under downward monotonic axial loading in undrained conditions, the original BT-1000 configuration mobilizes resistance through a combination of end-bearing at the tip and shear transfer along the shaft and fin surfaces. The computed ultimate axial capacity normalized to its self-weight for this baseline configuration is approximately 5.76 [2]. Failure is governed by a global cylindrical–conical shear mechanism extending upward from the tip, with a continuous plastic zone surrounding the lower embedded region, as seen in Fig. 5.

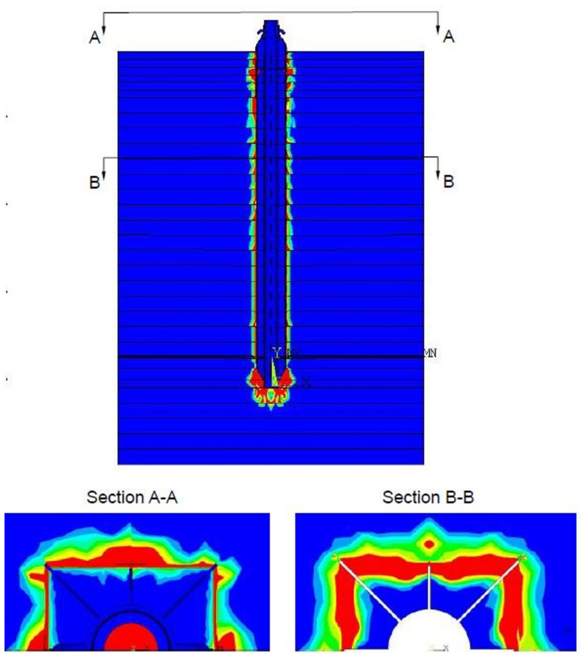


Fig. 5. Failure regions (in red) in the BT-1000 [2].

When the secondary fins are removed, the normalized ultimate axial capacity increases to 5.93, as shown in Fig. 6, which presents the variation of the normalized axial displacement (ratio between the axial displacement and the shaft diameter) with the normalized axial capacity by itself weight.

Modification 1 is 13% lighter, and a 10% reduction in axial capacity is observed. This aspect confirms that the secondary fins contribute as supplementary shear interfaces rather than controlling elements of the load-transfer mechanism. The global failure mechanism remains unchanged, with plastic strains concentrating along the shaft–soil interface and near the primary fins before coalescing into a continuous shear surface, as shown in Fig. 7.

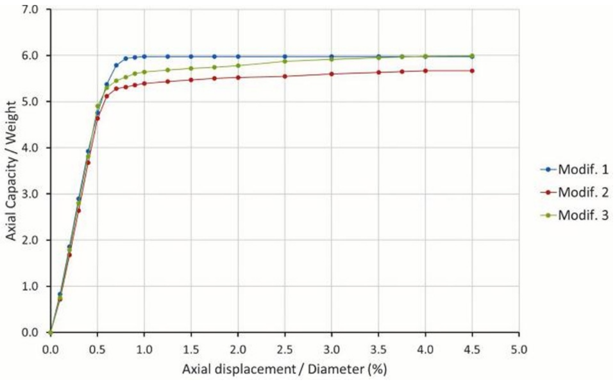
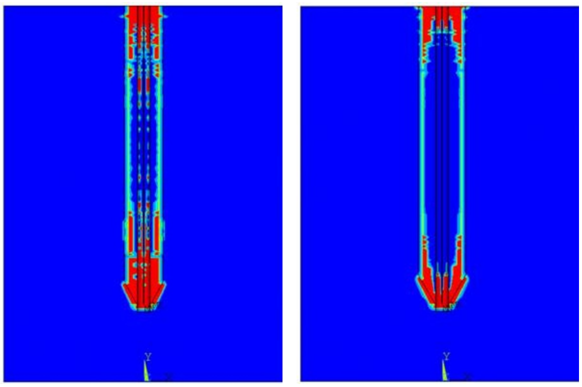


Fig. 6. Normalized axial displacement vs. Normalized axial capacity.



(a) (b)

Fig. 7. Failure regions (in red): (a) Modif. 1 and (b) Modif. 2 and 3.

In contrast, increasing the fin width and thickness produces a different effect. For modification 2, the normalized ultimate axial capacity almost equals the original. The modification is 13% heavier and a 13% increase in the axial capacity is noted. For modification 3, the normalized ultimate capacity increases to approximately 6.0, corresponding to an overall gain of about 20% compared to the original base. These increases are larger than the variations observed solely due to the removal of secondary fins.

The enhanced capacity associated with wider and thicker fins is attributed to three primary mechanisms: (i) increased projected shear area, which directly increases mobilized undrained resistance; (ii) greater confinement of the surrounding clay, leading to higher mobilized shear stresses before full plasticization; and (iii) increased structural rigidity of the fins, reducing local deformation and enabling more efficient stress transfer to the soil. The stress and plastic strain contours (Fig. 7) confirm that, in the enlarged-fin configurations, the plastic zone expands radially and vertically, forming a broader shear envelope around the embedded region. Although the overall geometry of the failure surface remains cylindrical–conical, its extent increases, and the mobilized shear stresses are higher over a larger volume of soil.

The influence on initial axial stiffness is also substantial. Although the removal of the secondary fins leads to a reduction in the initial axial stiffness, increasing the fin width and thickness results in a noticeable improvement in the small-strain stiffness. The percentage variations associated with each modification are summarized in Table 2.

Table 2. Modifications and corresponding increase/decrease in small-strain stiffness.

Modification	Stiffness increase/decrease
1	-10%
2	+18%
3	+30%

Overall, the comparative assessment demonstrates that removal of secondary fins has a limited impact on ultimate axial capacity (below 10%), whereas increasing fin width and thickness yield substantial gains of approximately 20% in ultimate resistance. Table 3 summarizes capacity results.

Table 3. Corresponding normalized and ultimate axial capacity after modification.

Modification	Normalized to its self-weight ultimate axial capacity	Ultimate axial capacity Increase/Decrease
Baseline	5.76	0%
1	5.93	-10%
2	5.66	+13%
3	6.00	+20%

The governing failure mechanism remains a global shear mode controlled by combined tip resistance and cylindrical shear along the embedded length, but geometric enlargement of primary fins significantly increases the mobilized soil volume and the efficiency of load transfer.

These findings indicate that, under axial loading in soft marine clays, structural optimization through enlargement of primary fins is considerably more effective than reliance on secondary fins for improving ultimate capacity.

5 Experimental study

An experimental study using large-scale Torpedo Base models is under development to enhance understanding of the mechanisms involved, and to inspect and review the findings from the numerical analyses.

First, three models of BT-1000 in scales 1:5, 1:10, and 1:20, designed to replicate both geometric and operational features of full-size Torpedo Bases were built. The scales were selected to study the scale effects.

The clay layer thickness at the Sarapuí II test site was evaluated in each case to ensure no boundary effects. The models were installed by both free-fall (Fig. 8) and static loading. In the case of free-fall, different heights and impact velocities were tested to calibrate penetration predictions and to simulate operational conditions.

Strong winds significantly affected the free-fall drop tests. The presence of gusts increased the risk of exceeding the maximum allowable vertical inclination of 1° during descent, potentially compromising the accuracy of the expected operational condition.

Fig. 8. BT-1000 Model (1/10 scale) launching in Sarapuí II test site.

The target penetration was at least 80% of the length. The obtained values are presented in Fig. 9, for the models on the three scales. It was possible to define the drop height to be used in other cases.

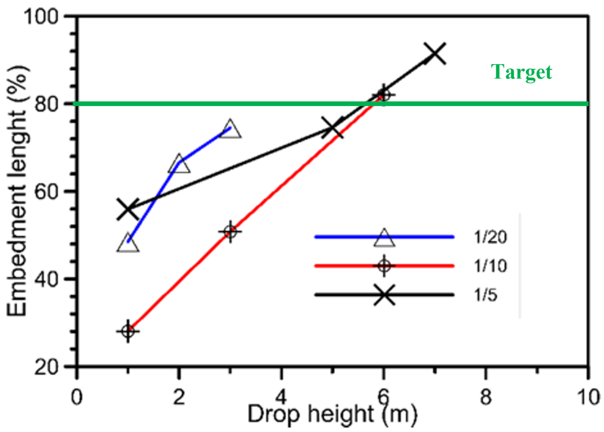


Fig. 9. Penetration length (as percentage) versus drop height for the 3 models used in different scales.

After installation, the bases were subjected to pull-out (tension) and compression load tests, immediately and after time intervals, to assess set-up effect.

An example of two pull-out tests is shown in Fig.10. For the model in scale 1:5 and the drop height of 7 m, the tests have been carried out 3 h and 43 h after installation. The gain in strength was quite significant, 40%, even considering that the penetration length of the base with higher capacity had a greater penetrated length (89% against 78%), the difference attributed to local variations of the soil profile and inclination during launching).

In all cases until now, the models have not been instrumented, thus the stress conditions around the base could not be evaluated. Total stress cells and pore pressure cells will be used to verify which contribution may be considered more important in the set-up effect: thixotropy, pore pressure dissipation and stress variations after pore pressure dissipation.

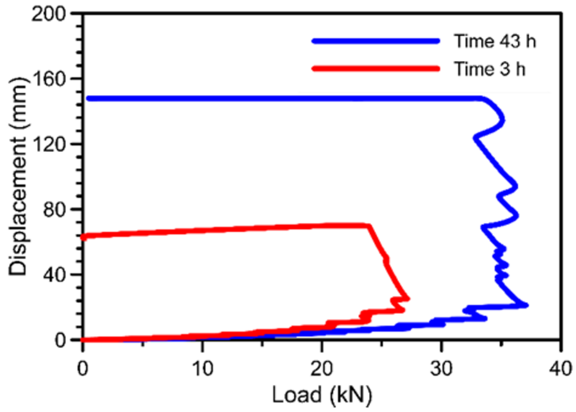


Fig. 10. Load versus axial displacement, uplift tests.

However, noteworthy findings were observed after removing the base from the ground. When the test was carried out after 3 hours of installation, only a very thin layer adhered to the base. After 43 h a significant soil layer (4 cm at the place indicated in the figure) was found adhered to the base, as illustrated in Fig. 11. Total fin width was 10 cm. It may also be shown that the soil thickness adhered to the top of the model was larger at that part, suggesting a faster rate of pore-pressure dissipation in that specific region.

Fig. 11. Soil adhered at the base surface after retrieval from the ground. Test carried out after 43 h installation.

These findings are in line with [2] where they state: "Hence, in order to compute the axial holding capacity of the base analytically, the α-method [13] should be used considering the square shape of the failure section as the base section"[2].

Static (jacked) installation is generally used to study the behavior of torpedo piles (also a driven pile). The present study further sought to determine whether this configuration represents an appropriate technical choice to represent a dynamically installed pile.

A preliminary test has been conducted, in which a torpedo model in scale 1:10 were installed, statically and by free fall, and then subjected to compression tests. Fig. 12 presents the corresponding results, in which it is shown that the capacity in compression of the base installed statically was almost 70% greater than the capacity of the base installed by free fall, despite the set-up time being only 1.2 h in the jacked case versus almost 3 h in the free fall case.

Although the base with higher capacity reached its total length during installation and the other base only 78%, the difference is too high to indicate that the installation procedure affects the base capacity. Such conclusion must be verified in future tests, due to its importance to extrapolate data from static installation to free fall installation.

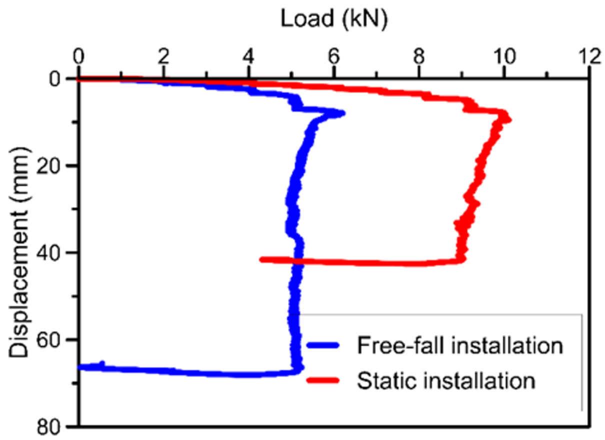


Fig. 12. Load versus displacement, compression tests.

Torpedo base models will be instrumented for obtaining data regarding the stress state in the base during both installation and retrieval. For this purpose, the bases will be instrumented with total stress cells and pore pressure cells.

However, before going directly to the base model's instrumentation, specific probes have been designed aiming to isolate the contribution of the fins in the whole capacity of the base, in which the shaft plays a significant role, as seen e.g. in numerical analysis. Fig. 13 shows one of these probes, in which four Kyowa miniature total stress cells have been installed.

The position of the cells was chosen to try to measure the total stress variation in length and width. Figs. 14 and 15 present the results obtained during static penetration and extraction (immediately after penetration) of the probe with the rate of 20 mm/s, the same used in piezocone testing.

The initial position of the probe was at its base at ground level. This means that the position of total stress cells were 0.15 m and 0.50 m above the ground level for total stress cells CTT1-CTT2 and CTT-3-CTT4 respectively. Since the water level was 0.53 m above ground level, CTT1-CTT2 were subjected to 0.38 m of water column and CTT3-CTT4 to 0.03 m.

The total stress cells were zeroed at the very beginning of the test; thus, the values above were added to the total stresses measured in all cases.

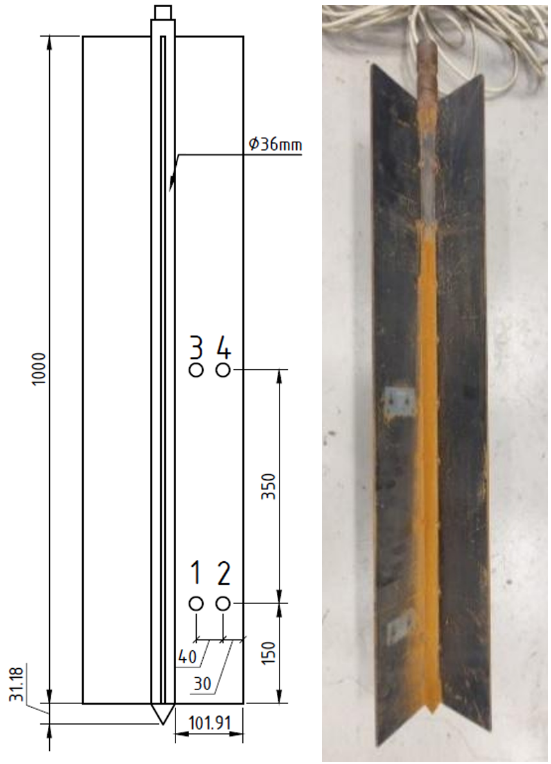


Fig. 13. Instrumented probe with miniature total stress cells (dimensions in mm).

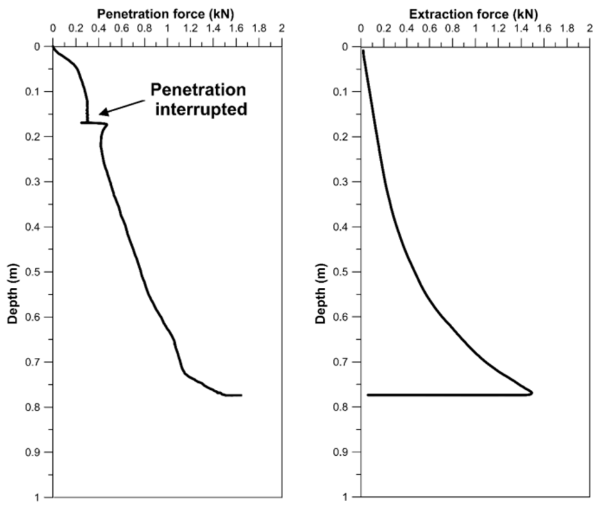


Fig. 14. Force measured during penetration and immediate extraction.

A particular pattern can be observed on Fig. 15. The total stresses measured by the internal cells (CTT1 and CTT3) were almost identical. CTT2 presented a trend of smaller values with respect to CTT1 and CTT4 higher values than CTT3. It was therefore found that there is an influence with respect to the stress changes along the fin width. However, the internal cells did not seem to have been influenced by the penetration as much as the external cells did, which seems to indicate higher stress increase as more soil volume is displaced during probe penetration. Regarding extraction, another interesting picture was observed. CTT1, the internal lower cell presented the smallest values, even negative in some places, indicating suction due to the trend of closing the space left by the probe. CTT2 presented higher values than CTT1, showing higher influence of the internal part of the probe in this retrieval mechanism.

Although pore pressures were not yet measured in these initial tests, there is at least an indication that the uplift capacity of the probe (also a pile) may be different from the capacity in compression, since the shear stresses depend on the horizontal effective stresses.

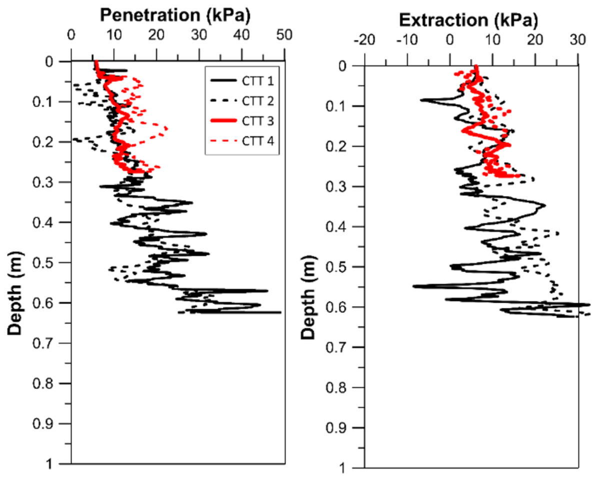


Fig. 15. Total stresses measured during probe installation and extraction. (see symbols on Fig. 13).

6 Discussion and conclusion

The study presented, in its actual status, has already shown, both by numerical analysis and experimental evidence, that there is an indication that the long-term torpedo base capacity must consider a square section involving the fins in the geometry to assess skin friction via analytical methods. However, this conclusion is valid only in the case of long-term capacity, because experimental evidence indicates that, in the short term, the remolded clay does not have sufficient time to regain strength and adhere to the base wall after the shear induced during installation.

Therefore, the study must continue to verify the relationship between soil adherence (plugging) and time to define the optimum section for consideration of skin friction. The overall soil-structure interaction should also be better understood for the application of the analytical methods.

It is generally assumed that piles driven statically and those installed by free fall exhibit similar behavior. However, this assumption is being re-examined, as an isolated test presented here suggests that it may not be valid. It has also been considered that the capacity of piles in soft clays is the same in compression and in tension (uplift). Few tests indicated that this may not be the case.

6.1 Numerical analysis

Numerical analysis has shown that secondary fins do not have a significant impact on the capacity of the BT-1000 Torpedo Base. Increasing the lateral area by adding secondary fins does not yield the expected improvement in capacity. On the contrary, it may introduce issues related to soil adhesion and increased material usage, which do not provide a corresponding performance benefit and may be removed. Increasing primary fins width and thickness may be a better approach. The consolidated conclusions about geometry, weight and capacity changes are presented in Table 4.

Table 4. Geometry, Weight and Capacity Variation.

Modification	Geometric Change	Self-Weight Variation	Capacity Change
Baseline	Original geometry with 8 fins (4 primary + 4 secondary)	—	0%
Mod. 1	Secondary fins removed	**–13%**	−10%
Mod. 2	No secondary fins; primary fins **+33% width**, **+56% thickness**	**+13%**	+13%
Mod. 3	No secondary fins; primary fins **+42% width**, **+56% thickness**	**+16%**	+20%

6.2 Experimental study

Three models of BT-1000 torpedo base in scales 1:5, 1:10, and 1:20, designed to replicate both geometric and operational features of full-size torpedo bases, have been manufactured and subjected to tests at the Sarapuí II international reference soft clay test site. Free fall tests have been carried out to calibrate the drop height necessary to reach a target penetration of at least 80% of the base length without hammering. Initial load tests have been carried out to compare uplift and compression behaviour as well as to preliminary investigate the set-up effect. It was observed that a soil layer adhered at the base, showing that the base capacity must consider a section different from the contour of the fins to assess the skin friction. It was also shown that the thickness of this adhered soil layer depends on the time after installation. Therefore, more studies are necessary to optimize the design and verify the optimum area to be used. In the present status, the conclusion from the numerical analysis is recommended, i.e. to use a square section for such purpose. A probe was designed and instrumented to isolate the contribution of the fins in the whole capacity of the base, in which the shaft plays a significant role. It was found that the total stresses were influenced by the position of the cell, both in length and width. However, the internal cells have been less influenced than the external cells with respect to the vertical position. Although without pore pressure measurements, a comparison between total stresses in penetration and extraction may indicate that the capacity of piles is different in compression and in tension.

6.3 Upcoming

Future work shall include tests with instrumented large-scale base models measuring total stress and pore pressure and the evaluation of set-up effects through effective-stress analysis. Cyclic lateral loading tests, scale-effect evaluation, assessment of the performance in soils containing sand lenses, and consideration of temperature and viscous effects, may also be addressed. Finite-element studies will be kept calibrated against all field data collected.

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