Numerical modelling of a soil structure interaction for a torpedo base conductor in a petroleum well under an extreme lateral load

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Abstract.

This work aims to compare the performance, regarding the soil structure interaction, of a torpedo base conductor and a jetted conductor, considering a drilling rig drift-off scenario. This can be considered an extreme load scenario and the results will be shown for lateral loads coming from the interaction between the wellhead and the drilling rig, drilling riser and BOP.

A complete 3D CAD model of the Torpedo Base Conductor was created and the soil was also modelled with 3D elements. Based on previous references, the selected 3D soil element was the Drucker-Prager constitutive model. Notably, the Drucker-Prager model accounts for non-homogeneous soil, meaning that the material properties vary with depth according to its undrained shear strength profile.

The final results show the behavior of soil under lateral loads for both the torpedo base and the jetted conductor, as well as the structural response. The final conclusion is that the torpedo base has a better performance under lateral loads than the jetted conductor and can be considered a good well foundation solution to mitigate problems associated with interventions with dynamic position drilling rigs in shallower water depth.

Keywords: torpedo base, lateral load, 3D numerical model.

1 Introduction

1.1 Contextualization

Torpedo base is a proprietary conductor installation method developed in Petrobras by Nogueira et al. [1]. According to the authors, this development was based on the success of using torpedo anchors as mooring systems for Production Platforms. The process consists of either driving the torpedo base with its self-weight or launching it from a certain height above the seabed to use gravity acceleration to obtain a higher energy of impact, in order for it to reach a deeper penetration. The deployment of the torpedo base has the advantage of being done with an Anchor Handling Tug Supply (AHTS) vessel, which has a much smaller daily rate when compared to drilling rigs.

Figure 1 shows a CAD model of a torpedo base as long as some pictures of the equipment being handled in a storage area and in the deck of an AHTS.

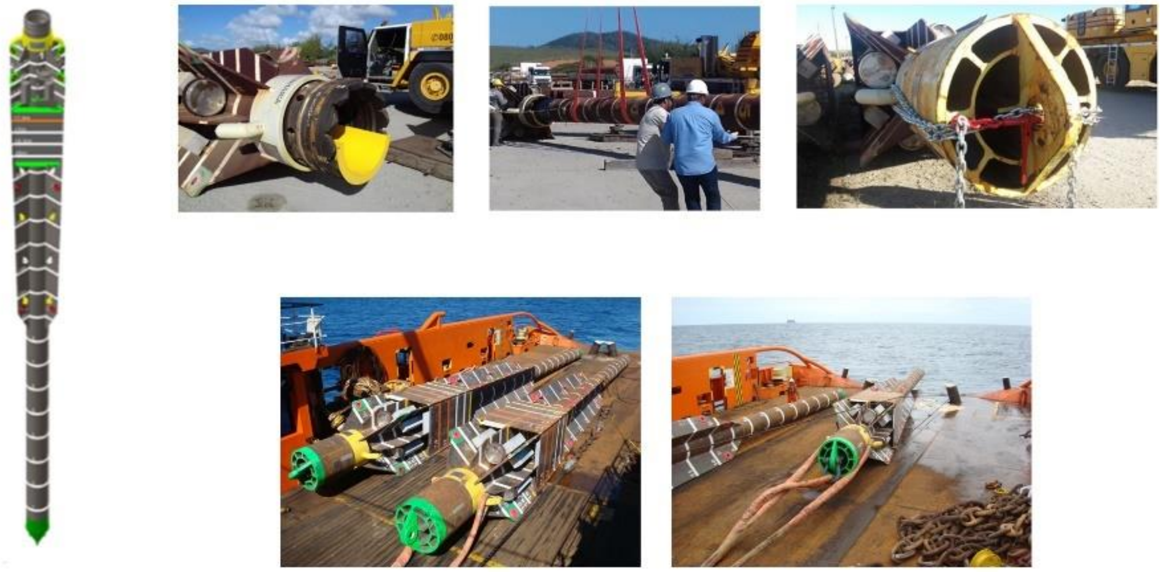

Figure 1. Pictures of a torpedo base being handled and in the deck of an AHTS vessel. (Source: Petrobras)

The mostly used conductor installation technique worldwide is the jetting. In this methodology, the first two sections of the well are drilled in a single trip operation. The conductor is assembled with a jetting bottom hole assembly (BHA), generally composed by a drill bit (PDC or tricone), a mud motor (to provide rotation) and some drill pipes. This BHA stays fixed to the conductor during the whole jetting operation by a running tool that allows it to be released from the conductor when it reaches the final depth, so the same BHA can drill ahead the second section of the well, see [2] [3] and [4].

Due to this optimization of constructing the first two sections of the well in a single trip, the jetting technique is one of the most economic solutions for the top hole design. However, when comparing these costs with the ones for the torpedo base, the jetted conductor can reach four to ten times the value. This shows that the torpedo base is by far the most economic top hole solutions in the industry and that's why it is the focus of this work.

In the work here developed, which addresses a foundation design problem, an application of FEA is employed to understand the interaction between the soil and the foundation. A commonly used constitutive model for the soil behavior is an extension of the Winkler's hypothesis in which the soil is represented by nonlinear horizontal springs along the length of the pile, those springs are represented by the so-called p-y curves. For offshore applications, the industry in general complies with the recommendations for laterally loaded piles from API RP 2GEO [5]. Some examples of application of p-y curves in finite element modelling of conductor casings can be seen in [6] and [7], for as for offshore wind turbines and piles in general, see [8], [9] and [10].

Torpedo bases have a more complex geometry when compared to usual cylindrical shaped foundations, so the p-y curves approach becomes not suitable to evaluate the behavior of the soil around the foundation, this would be a good approach for an axisymmetric problem. Therefore, a 3D finite element analysis was chosen to model this case, with 3D soil elements, to better understand the distribution of stresses for both the torpedo base structure and the soil around, and its possible implication regarding the lateral resistance. One of the most commonly used FEA models for underwater soil modeling is the Drucker-Prager model, which was also selected in this work, see [11], [12], [13] and [14]. This model allows for shear analysis of soil based on parameters such as friction angle, dilation angle, among others. It is applied to assess soil flexibility, estimating its bearing capacity and deformation under different conditions and, also, the analysis of failure wedges associated to transversal loads, which can be seen in Figure 2, where a failure wedge is shown in a 3D finite element post processing [15]. The same type of analysis of failure in laterally loaded piles can be, also, seen in [16].

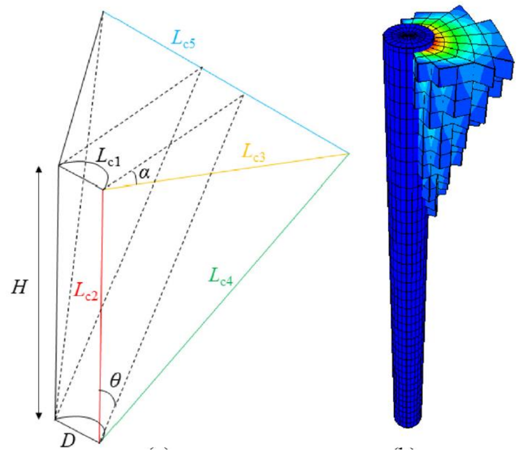

Figure 2: Example of analysis of a failure wedge, showing a theoretic scheme and a 3D finite element post processing for a cilindrical foundation [15].

1.2 Problem definition

The context of this work is a drift off analysis for a dynamic positioning drilling rig, which supposedly had a blackout, and its interaction with a subsea wellhead under an extreme load scenario [17]. This extreme scenario corresponds to loads coming from the year's statistical greatest winds, waves and currents all aligned to the same direction, as shown in Figure 3. In the same context, a restriction diagram could be defined, considering some characteristics of the dynamic positioning system and some statistical data regarding the blackout occurrences [18].

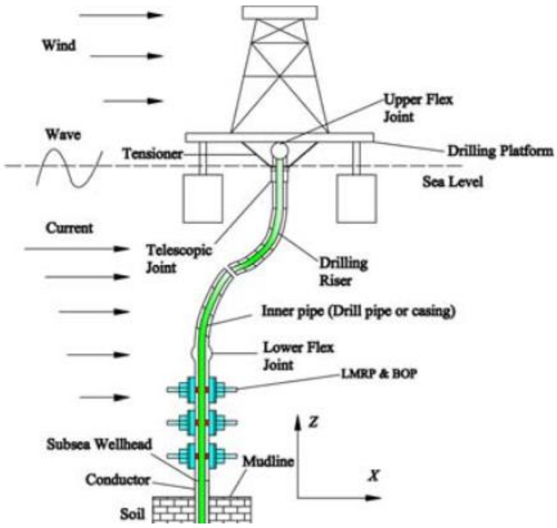

Figure 3: Schematic of a fully coupled drift off analysis in a dynamic poistioning drilling rig [17].

This work aims to evaluate the performance of the torpedo base compared to jetted conductors in a drift off analysis, in order to help well designers to decide between these two conductor installation methodologies. This is particularly important when it comes to the use of MODU drilling rigs in shallow and deep water depths, where the interaction between the drilling riser and the wellhead generates greater loads. It is important to highlight that the decision of the best foundation solution must not be driven only by the lateral load resistance and by the costs involved and, for the torpedo base, by the evaluation of the driveability of this type of foundation according to the soil properties of the well location. The evaluation of the lateral load resistance will be made taking into account both the lateral displacement and the possibility of failure of the soil wedge mobilized by the lateral displacement.

2 3D Finite Element Model

2.1 Mathematical Modeling

The mathematical model is based on the hypothesis of highly cohesive clayey soil, commonly found in offshore seabed. Based on the study conducted by [11], it was possible to determine the elastic behavior of the soil, allowing the Young's modulus of the soil to be defined as:

$$E = 275.Su(z)\ \text{(Pa)} \tag{1}$$

Where Su(z) is the undrained shear strength curve of the soil. Also based on [11], the Poisson's ratio has an assumed constant value of:

$$v = 0.49 \tag{2}$$

Regarding plastic behavior, the Drucker-Prager model was chosen due to its relevance to the problem and its extensive use in the literature. The study [12], based on the same hypothesis assumed here of purely cohesive soil, establishes the equivalence between the Drucker-Prager and Huber-von Mises models, which consequently allows for the assumption of the following values for the soil internal friction angle, dilatancy angle, cohesion, and yield stress:

$$\theta_{fric} = 0° \tag{3}$$

$$\theta_{dil} = 0° \tag{4}$$

$$c = Su(z) \tag{5}$$

$$\sigma_Y = 2c \tag{6}$$

The approach used was the modeling of a multi-layered soil, where some characteristics vary according to the Su(z) function, which in turn varies with depth z. The curve used is shown in the equation below:

$$Su(z)[\text{Pa}] = 2400(z) + 2700 \tag{7}$$

2.2 Numerical Modeling

The presented models were constructed using the Abaqus software. For soil modeling, C3D8H elements were used, which are hybrid elements. These elements are particularly suitable for modeling saturated soils, as the high water content makes the material nearly incompressible. Firstly, hybrid elements help mitigate volumetric locking, a numerical effect observed in standard elements when modeling incompressible materials. Volumetric locking consists of an artificial increase in the stiffness of the element, leading to unrealistic pressures that do not align with actual physics. Hybrid elements avoid this by treating pressure as an additional degree of freedom, an independent variable, determined simultaneously with displacements, rather than as a consequence of them. This approach allows for a more accurate representation of the incompressible nature of saturated soils. Therefore, hybrid elements are essential for accurately capturing stresses and deformations in soil-structure interaction analyses. As mentioned, the modeled soil is of the multi-layer type. Cells of 1[m] depth with common characteristics were considered. The soil model is approximately 42[m] deep. Simulations of the jetted pipe in this soil and the torpedo base were then performed.

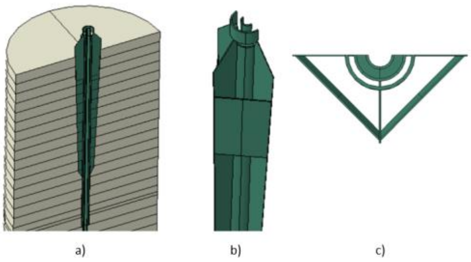

Figure 4: Multilayered Soil in Contact with Torpedo Base (a) Focus on Symmetry (b) Top View (c)

It was possible to simulate a complete 3D model of the Jetted Pipe case, as shown. For the model containing the torpedo base, a symmetry model was used due to the geometric complexity and the extra computational cost, which implies seeking simplifications. Below, you can see the meshes of both scenarios:

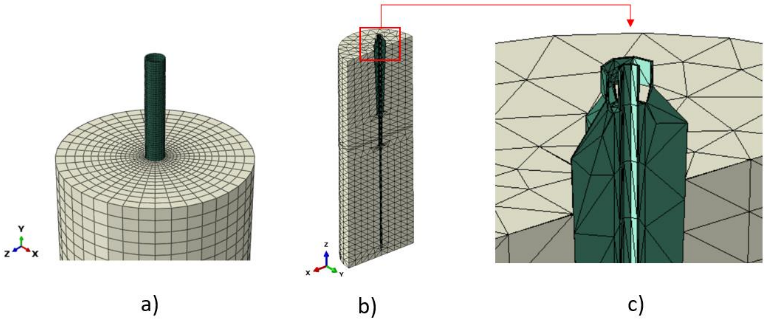

Figure 5: Jetted Conductor Mesh (a) and Torpedo Base Mesh (b) Zoomed View of Torpedo Mesh (c)

3 Results

A bending moment of 2401.175 [kips.ft] was applied to the upper end of the models. For the jetted conductor simulation, a displacement of approximately 10.8 [cm] in the top of the wellhead in the top of the wellhead was observed.

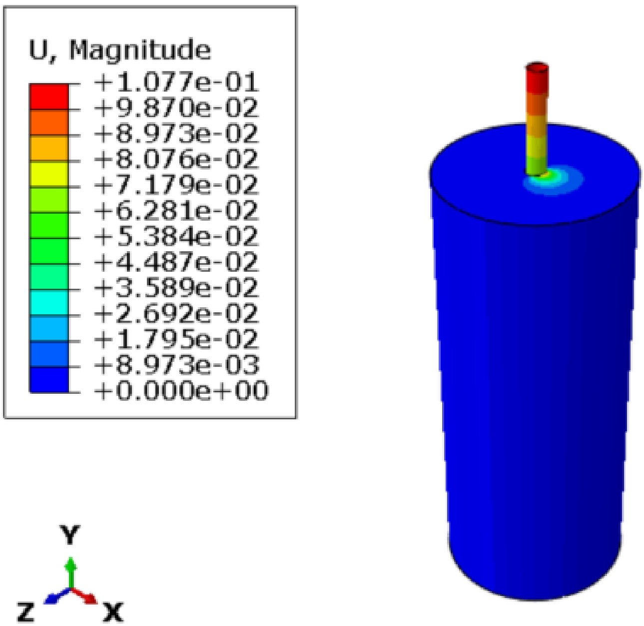

Figure 6: Jetted Conductor Results

For the Torpedo Base case, a smaller displacement of about 3.08 [cm] was observed.

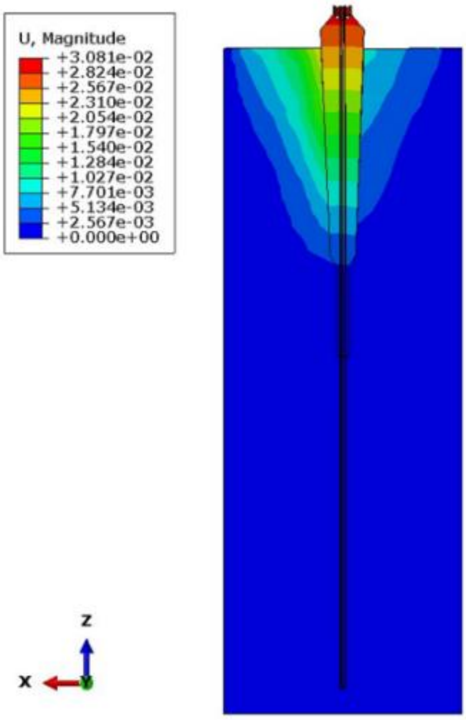

Figure 7: Torpedo Base Case Results

Thus, a greater lateral capacity of the Torpedo Base is observed. This is explained by its more complex geometry, including a geomechanical brake in the top, this geometric feature is important to guarantee that the torpedo base does not sink into seabed during the installation. The primary reason for expecting less displacement of the Torpedo Base compared to the jetted case is that, when loaded laterally, the Torpedo Base mobilizes a much larger soil area than a smooth pipe due to the presence of fins and the geomechanical brake. This significantly increases the stiffness of the system. The fins and the brake work together to create a more extensive interaction with the surrounding soil, distributing the load over a larger area and thereby enhancing lateral stability.

Additionally, by mobilizing a larger wedge area, the resistance of the soil to lateral loads is greatly increased. This means that the soil provides a higher level of opposition to any lateral movement of the base, ensuring that the structure remains more firmly in place. The increased lateral resistance is a crucial factor in the improved performance of the Torpedo Base, as it directly correlates with the reduced displacement under load. Consequently, the enhanced design of the Torpedo Base not only brings more economy to the top hole construction but also provides long-term lateral stability and reliability in the field. The figure below illustrates the post-processing of the mobilized soil wedge for the jetted case (a) versus the Torpedo Base (b). Despite geometric differences, with the Torpedo Base modeled using tetrahedral elements and the jetted case using purely hexahedral elements, it is evident that the Torpedo Base mobilizes a larger soil wedge.

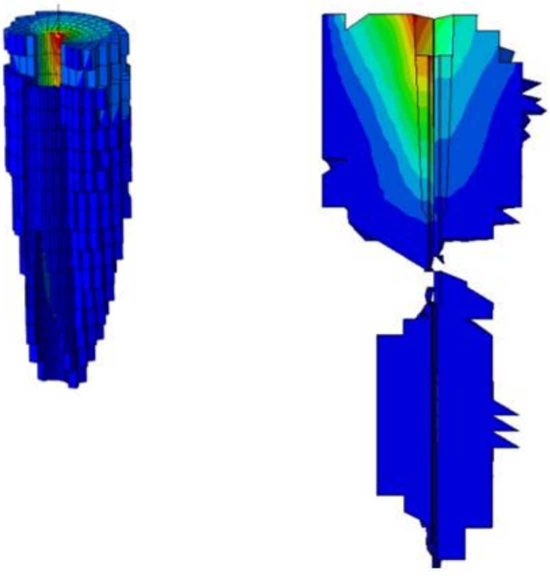

Figure 8: Torpedo Base Case Results

4 Conclusions

The Torpedo Base presents a significant advancement in conductor installation methods, particularly in its lateral. This design mobilizes a larger soil area, increasing system rigidity and foundation resistance to lateral loads, implying in a smaller lateral displacement and generating less stresses in the foundation. These technical advantages, combined with the economic benefits, make the Torpedo Base a good solution for the optimization of the top hole. It is important to highlight that the torpedo base requires the cement job in the surface casing to reach the seabed, in order to provide sufficient axial capacity for the whole well lifecycle.

From an economic perspective, the Torpedo Base method offers a substantial cost advantage. The deployment process utilizing an Anchor Handling Tug Supply (AHTS) vessel drastically reduces daily operational costs compared to traditional drilling rigs. While jetting remains a widely used technique due to its efficiency in constructing the first two sections of the well in a single trip, the overall costs associated with jetting can be four to ten times higher than those of the Torpedo Base. This difference highlights the Torpedo Base as the most cost-benefit solution for top hole design in the industry.

5 References

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