

Numerical Analysis of the Effect of Fin Configuration on the Holding Capacity of a Torpedo Anchor

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Abstract: Torpedo anchor is a deep foundation used in deep water for anchoring various floating structure. This study investigates the effect of fin arrangement on the pullout response of a torpedo anchor in clay soil using PLAXIS 3D. The effect of length (Finless, $L/3$, $L/2$, $2/3 L$, and $0.9L$), width ($0.45d$, d , and $1.5d$), and shape of the fin (rectangular, delta, double delta, trapezoidal, and elliptical) on the capacity of the torpedo anchor were investigated. It was found that the fin length ($0.9 L$) and width ($1.5d$) provide the maximum capacity. The pullout capacity of the rectangular fin anchor was recorded as the highest at 1895 kN; however, the elliptical fin anchor had a slightly lower capacity of 1864 kN. This analysis is important for the design of a torpedo and helps in understanding the soil-anchor interaction.

Keywords - Torpedo anchor, fin configuration, pullout capacity, PLAXIS 3D.

INTRODUCTION

A torpedo anchor is a deep pile foundation used to anchor the floating structure in deep water. It is a long, cylindrical pile made of stiff material like steel and filled with scrap or ballast, as shown in Fig. 1 [1]. A torpedo anchor has a sharp tip, called a nose, that allows it to penetrate deeper into the seabed. It can be constructed with fins or without fins, depending on the design criteria. The advantage of a torpedo anchor over the other anchors is the self-penetration with free fall over long distances, creating a water column using kinetic energy. The free fall anchor, which resembles a torpedo, was first developed by Petrobras for mooring flexible risers and floating structures in 1996, and their first commercial application was in the Campos Basin, offshore Brazil, in 2000 [2]. The idea was expanded over the next few years into larger, finned anchors with greater holding power for mooring floating production units [2, 3]. The concept was also suggested by Lieng et al. (1999) as a deep penetrating anchor. The principal benefit of the torpedo-type anchors is their inexpensive and easy deployment. They require no external energy source during installation and suit deep and ultra-deep water, where other anchor types are costly [5]. But the verticality of the anchor after installation is not known, and this can have an impact on the holding capacity of the anchor.



Fig.1 Torpedo anchor

The geometry of the fins is still an important subject of study because the capacity is greatly affected by the shape of the fins as well as the stability of the anchor during a free fall. The numerical analysis of pullout capacity of torpedo anchor in clay soil was carried out using a non-linear three-dimensional FEM (ANSYS), taking into account the undrained analysis [6]. A non-linear FEM model was developed in ANSYS to estimate the capacity of the anchor under undrained conditions and to compare the results with the various full-scale tests [7]. Large deformation analysis of finite element analysis was carried out to estimate the torpedo anchor installation, taking the account post-penetration deformation [8]. Also, LDFA were conducted to predict the vertical and horizontal failure of the torpedo anchor with inclined loading [9]. Semi-theoretical methods were proposed to estimate the pullout capacity of torpedo anchors in clay soil based on the loading angle inclination [10]. Chen et al. (2016) performed a parametric study on the holding capacity of torpedo anchors in clay soil using the finite element method, considering the effect of loading angles. A dynamic analysis of an installed torpedo anchor was performed using the LDEF, taking the account the strain-rate effect method [12]. The pullout capacity of the torpedo anchor was studied using finite element analysis with full-flow pentameter modeling [13]. The holding capacity of a torpedo anchor is influenced by many factors, and one of the factors that significantly affects the capacity is the arrangement shape of the anchor. The optimal shape of the anchor is essential to understand the real behavior of a torpedo anchor.

This paper investigates the effect of fin configuration (length, width and shape) on the holding capacity of a torpedo anchor in clay soil using the finite element tool PLAXIS 3D. The examined lengths of the fin are (Finless, $L/3$, $L/2$, $2/3 L$, and $0.9L$). Three widths were simulated and examined, namely ($0.45d$, d , and $1.5d$). Five fin shapes were considered: rectangular, delta, double delta, trapezoidal, and elliptical. The effect of these configurations markedly affects the holding capacity; therefore, it is essential for the researcher to understand the response of a torpedo anchor with various fin configurations. The numerical characterization of the fin configuration with various parameters in relation to pullout capacity remains an active and evolving area of study.

NUMERICAL MODELING METHODOLOGY

Torpedo anchors were modelled using the finite element tool PLAXIS 3D for predicting the holding capacity response of torpedo anchors with different fin configurations. The field torpedo anchor by Medeiros, (2002) was modelled using PLAXIS 3D, having dimensions of 12 m length, 0.762 m diameter, and a mass weight of 240 kN, penetrating a seabed to a depth of 20 m. The water depth in the Campson Basin field, Brazil, was 1300 m, with a normally consolidated clay having a soil profile ($s_u = 5 + 2z$), where s_u is the undrained shear strength and z is the depth below the seabed. The cohesion and the angle of internal friction of the NCC soil in Campson Basin are 5 kPa and 17° .

3.1 Model Geometry (Sensitivity analysis)

Initially, sensitivity analysis was performed to attain the optimal geometry of the soil model as well as to understand how the torpedo anchor models are influenced by the soil model geometry. The soil model is assumed square because the torpedo anchor is modelled symmetrically. Two key parameters were considered: width or length and the depth of the model. At the outset, the depth of the soil model is assumed to be constant, and the width is variable. The baseline reference for the width size is 6 m, which is around 8 times the anchor's diameter, and the corresponding maximum displacement of the anchor model is recorded. The width size of the model is consistently increased until a constant change in the output (displacement). The first constant value in the change in displacement is considered to be the optimal size of the soil model, which is 14m. Fig. 2 represents the sensitivity analysis for the soil model with respect to the change in the displacement of the torpedo anchor. Similarly, for the depth of the soil model, the initial depth is assumed to be 24 m, which is around 2 times the anchor's length. The first constant value of the depth size is 35m. The optimal size of the model anchor is 12m width/length and 35 m depth, as depicted in Fig. 3.

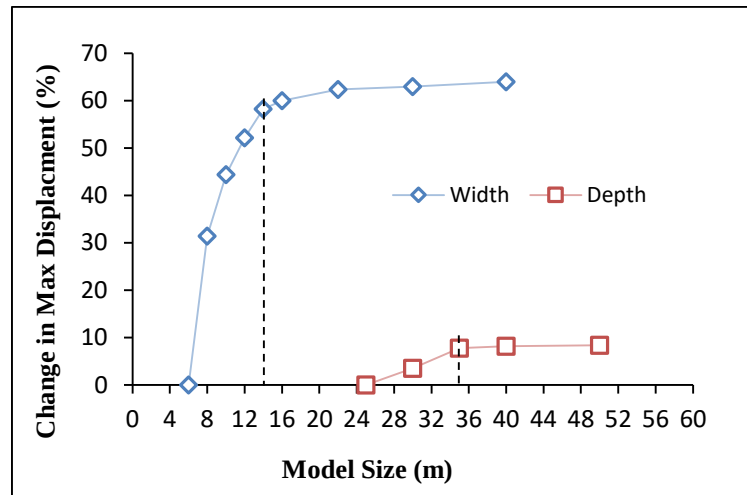


Fig. 2 Sensitivity Analysis for Model Geometry

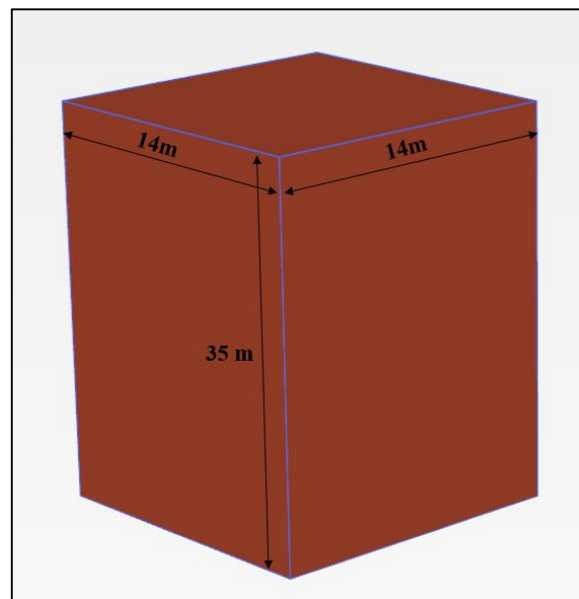


Fig.3 Soil Model Dimension

3.2 Soil constitutive model

The NCC soil of the Campson Basin was modelled using the Modified Cam-Clay (MCC). The MCC is an elasto-Plastic critical state model used for stress-dependent stiffness as well as the volumetric deformation of clay. This constitutive model mainly depends on the stiffness parameters, namely, compression index(λ) and swelling index (κ), and the strength parameter, slope of the critical state line (M_{CEL}). Table 1 shows the calibrated parameters used in this study for modeling the torpedo anchor.

Table 1 Soil model properties

Normally consolidated clay	
Model type	Modified Cam-Clay
Drainage type	Undrained A
Unsaturated unit weight	16.0 kN/m ³
Saturated unit weight	18.0 kN/m ³
Compression index (λ)	0.25
Swelling index (κ)	0.040
Slope of the critical state line (M_{CEL}).	0.5
Poisson's ratio	0.15
Cohesion	5.0 kPa
Angle of internal friction	17°

3.3 Torpedo Anchor Models

After modeling the soil model, the torpedo anchor pile is modeled using volume elements. A polycurve with a radius of 0.381m is drawn, and a surface is constructed to extrude the shaft volume to a length of 11.34m. The total length of the anchor is 12m; the nose, or the conical tip of the anchor, is constructed with a 0.66 m length using the command (cone 0.381, 0.66 (0, 0, -11.34) (0, 0, -1)). The fins are also constructed as a volume element: a surface is initially created and then extruded to a thickness of 10 cm. The fins, shaft, and the nose are then combined as a single mass element (volume element). The soil is assigned to the torpedo anchor using a linear elastic model. Table 2 presents the properties of the torpedo anchor as a steel volumetric element. Subsequently, in the anchor model, the anchor is assigned as a rigid body to avoid structural deformation (i.e., an incompressible pile). The anchor model is thereafter decomposed into surfaces to create an interface element between the soil and the anchor pile. The interface material is an element constructed between the anchor and the soil. It allows relative slippage between the soil and the model rather than full bonding. The reduction factor (R_{int}) for the interface is 0.75.

Table 2 Torpedo anchor model properties

Torpedo Anchor	
Soil Model	Linear Elastic
Drainage Type	Non-porous
Unsaturated unit weight	78.5 kN/m ³
Modulus of Elasticity	30 x10 ⁶ kPa
Poisson's ratio	0.2

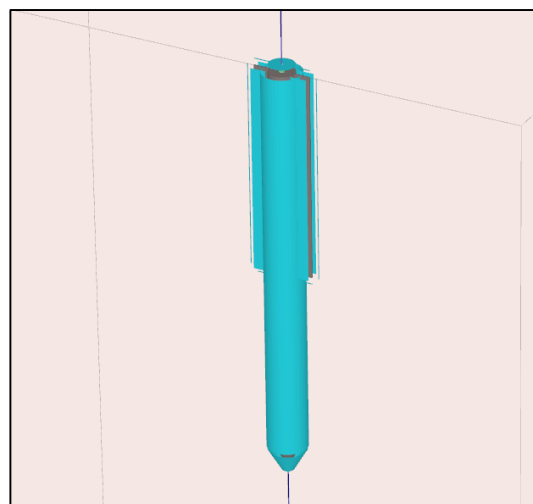


Fig.4 Interface element between soil and anchor model

3.4 Meshing and staged construction

The soil and the anchor are well modelled; thereafter, the mesh is generated. In this work, the selected type of mesh is a fine mesh, which is the optimal mesh. The anchor model is refined with a coarseness factor of 0.5 to improve the accuracy of the numerical solution. The anchor model has a complex geometry and very small edges, requiring a refined mesh. Fig.5 shows the mesh generated for the soil and anchor model. The last stage before running is the staged construction. It consists of three phases: the initial phase, the installation phase, and the loading phase. The initial phase includes the internal soil stresses and groundwater conditions, and the anchor model is deactivated. The second phase is the installation phase; in the phase, the anchor model, including its interface, is assigned. The last phase is the loading phase; the rigid body is assigned, and the required loading is applied in the corresponding direction. The load is applied purely horizontally at the top of the anchor, 8 m below the seabed. According to [Medeiros, \(2002\)](#), the load of 1400 was applied in the horizontal direction for the finless torpedo anchor, which is the baseline for this research. The numerical control parameter tool was Pardiso (multicore direct). Fig. 6 presents the staged construction with the representative phases.

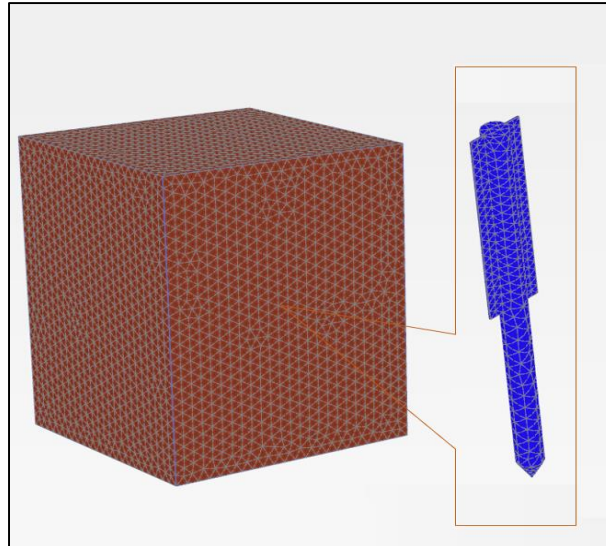


Fig.5 Mesh generation of the soil and anchor

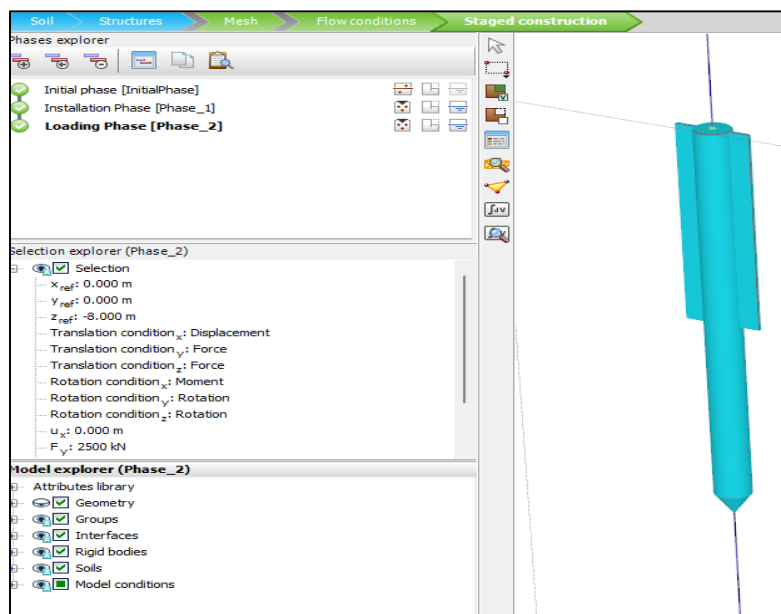


Fig.6 Staged construction

3.5 Parametric study

In this study, the effect of the length, width, and the shape of fins on the pullout capacity of a torpedo anchor is well investigated. Four different lengths are examined: $L/3$, $L/2$, $2/3 L$, and $0.9 L$, with a fixed fin width of 0.45 m ($0.6 d$), as shown in Fig. 7 (a). The baseline reference is the finless anchor, with a length of 12 m and a diameter of 0.762 m . The second parameter is the width of the fin, namely: $0.6 d$, d , and $1.5 d$ as depicted in Fig. 7 (b). The length of the fin in this case is constant at $0.5 L$, and the variable is the width. These 3 anchors are also compared with the baseline finless anchor model. The third parametric study is the shape of the anchor model; five different shapes of fins are modelled and examined. The fin shapes are rectangular, delta, double-delta, trapezoidal, and elliptical, as shown in Fig. 7(c). Fin geometry strongly influences the capacity of a torpedo anchor; therefore, the researcher must understand the behavior of a torpedo anchor with various fin geometries. Different fins may perform differently, especially in clay soil, and this may affect the penetration depth, which can affect how deep the anchor penetrates into the seabed. Therefore, it is essential to study the fin geometry with various aspects.

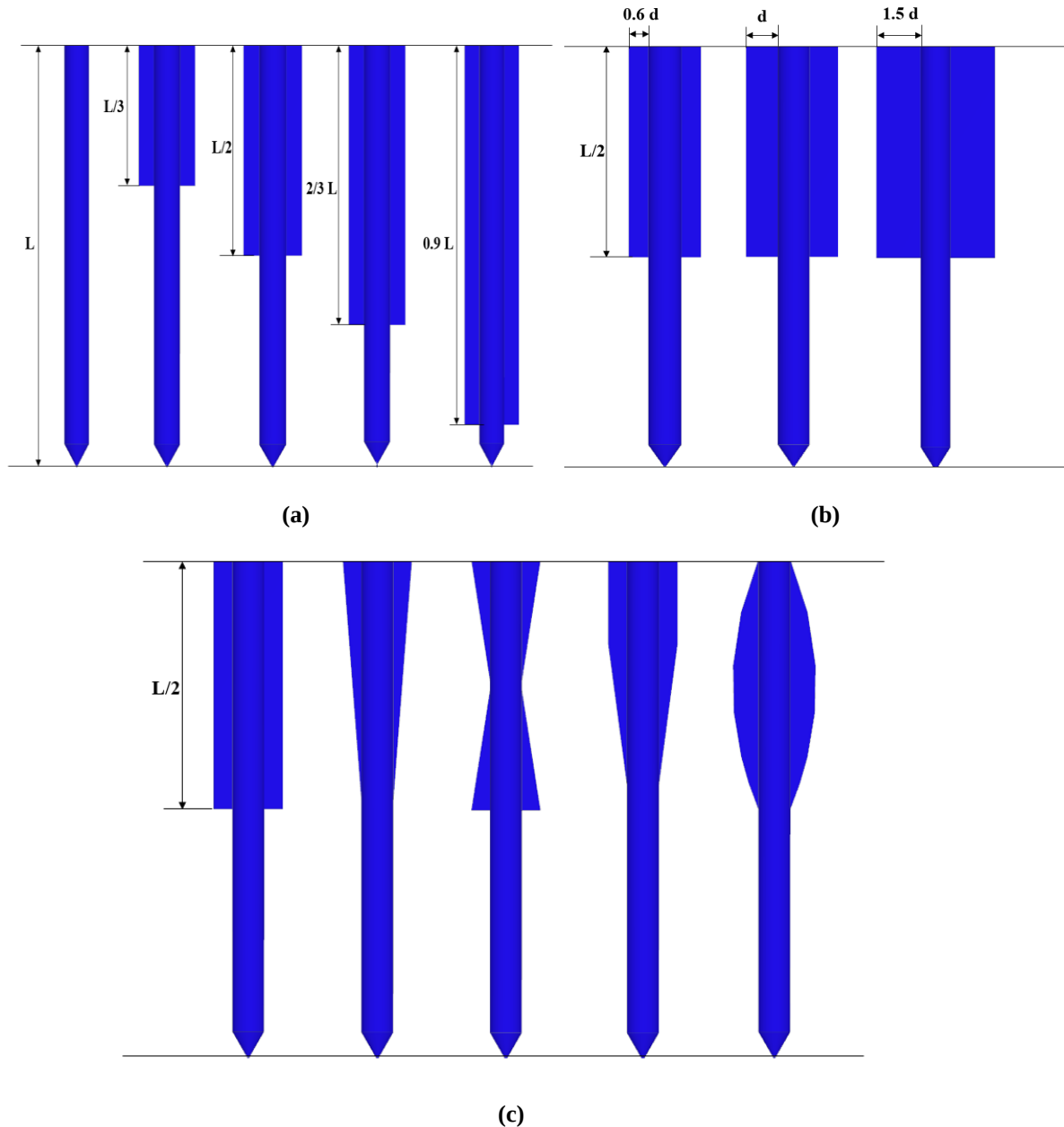


Fig.7, The parametric study: (a) length of fin, (b) width of fin, (c) shape of fin

RESULT AND ANALYSIS

4.1 Effect of fin length

In this study, the influence of four different fin lengths of anchor models, namely $L/3$, $L/2$, $2/3 L$, and $0.9 L$, is examined. Fig. 8 represents the load-displacement curves for the all cases; all curves follow a similar nonlinear pattern, since the modified cam clay model is used. The soil resistance is mobilized with no clear point of plateau; therefore, the holding capacity of the anchor follows the practice criteria of displacement corresponding to 10% of the pile anchor diameter (CEN, 2004). The 10% of the diameter (0.782 m) corresponds to 0.0782 mm. At the same displacement, the finless model anchor provides 1370 kN. By providing fins, the holding capacity consistently increased to about 1580, 1900, 2080, and 2430 kN for the fin lengths of $L/3$, $L/2$, $2/3 L$, and $0.9 L$, respectively. The percentage increase with reference to the baseline (finless anchor) is 15%, 39%, 52%, and 77%, respectively. The $0.9 L$ anchor recorded the greatest capacity because it has a larger bearing and frictional resistance area. The results revealed that the longer fin length provides a stiffer initial behavior of the anchor model. In general, the length of the fin has a great influence on the anchor's capacity. The normalized capacity ($P_{fin}/P_{finless}$) is plotted against the normalized length (L_f/L) as shown in Fig. 9. The holding capacity of the torpedo anchor increases by around 77% with reference to the finless anchor. The normalization curve shows a linear relationship, with a range of around $R^2 = 0.99$ and no sign of it leveling off as it gets longer. However, the thickness of the fin must be further studied due to the structural bulking which may occur in the longer fin with small thickness. This indicates that the increase in the fin length leads effectively to the anchor resistance.

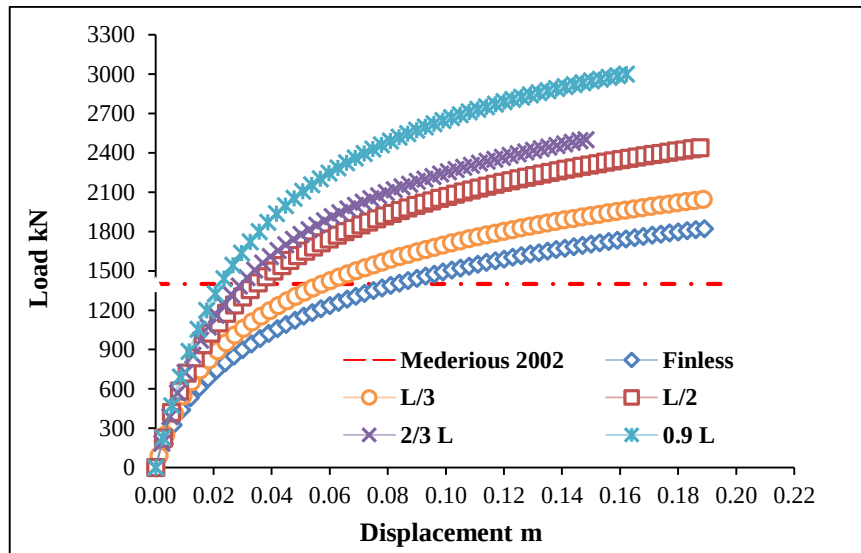


Fig. 8. Load-displacement curves for the effect of fin length on the holding capacity of anchor model

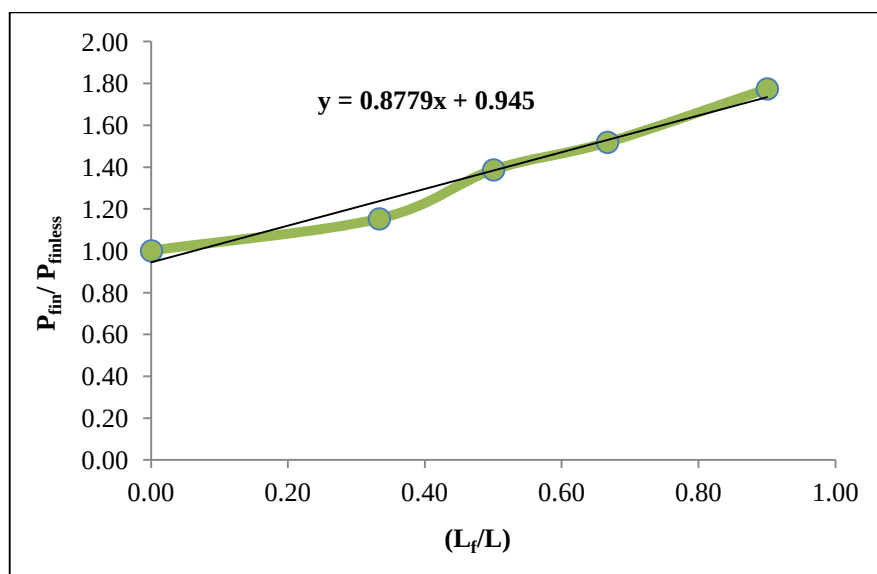


Fig. 9. Relation between the normalized capacity and normalized length of anchor models

4.2 Effect of fin width

The effect of the width of the fin on the capacity of the torpedo anchor is also an important parameter to be studied. Three widths were examined: 0.6d, d, and 1.5d. Fig. 10 shows the load-displacement curve for the effect of the width of the fin on the capacity of the anchor model. Similarly, the curves show a non-linear behaviour, and the plateau point is not well defined. The holding capacity of the anchor at the displacement of 10% of the anchor diameter is 1900, 2180, and 2630 kN for fin widths of 0.6 d, d, and 1.5d, respectively. The percentage increase relative to the finless anchor is approximately 39%, 39%, 59%, and 92% for fin widths of 0.6 d, d, and 1.5 d, respectively. The results show that wider fin widths improve the torpedo's capacity by increasing the bearing-resistance area. Overall, the 1.5d anchor model offers the highest capacity. Both the length and width of the fin significantly improve the capacity of the anchor models, but to varying degrees. The normalized capacity ($P_{fin}/P_{finless}$) is plotted against the normalized width (w_f/L) as shown in Fig. 11. The normalized capacity increases from 1.39 to 1.92 at 1.5d fin, which indicates that the wider fin contributes significantly to the increase in the holding capacity of the torpedo anchor. The analysis therefore provides a better understanding of anchor behaviour and supports a more efficient anchor design.

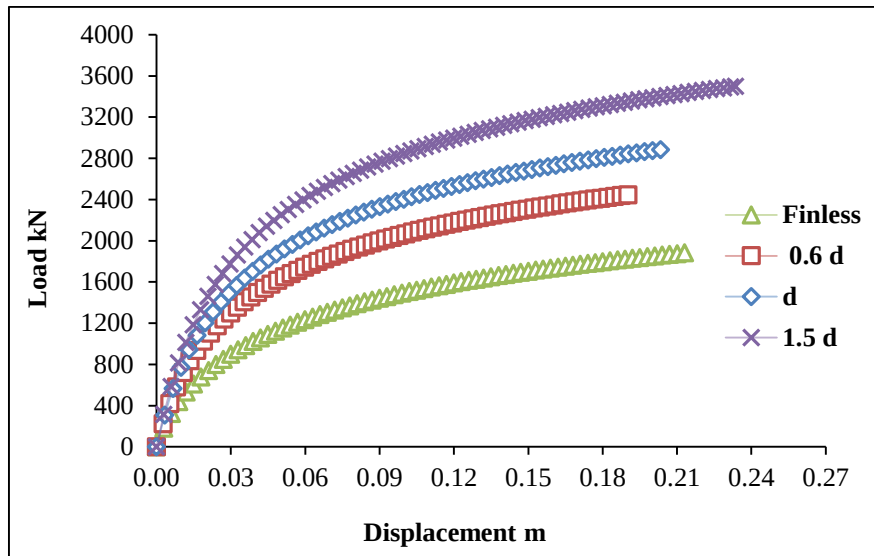


Fig. 10. Load-displacement curves for the effect of fin width on the holding capacity of anchor model

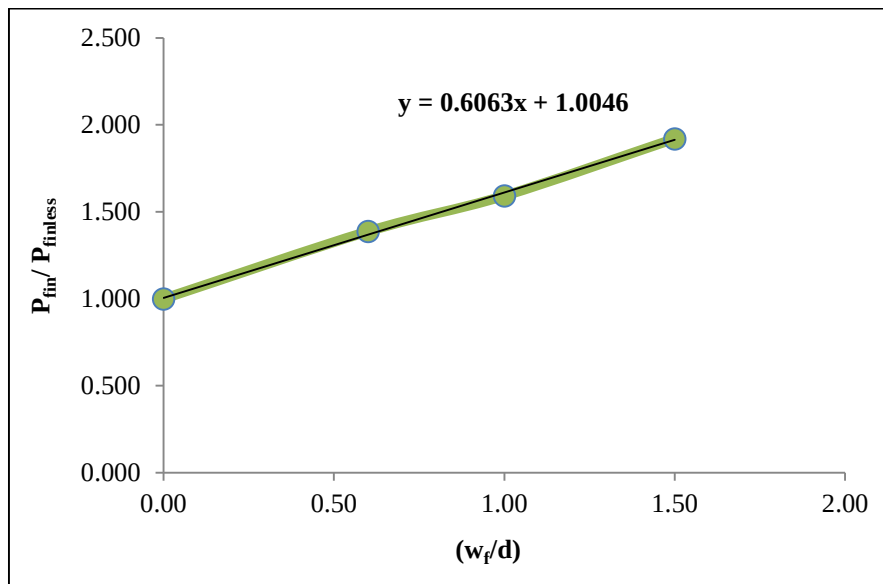


Fig. 11. Relation between the normalized capacity and normalized width of anchor models

4.3 Effect of fin shape

Fig. 12 shows the load-displacement curve for the effect of the shape of the fin on the holding capacity of a torpedo anchor. The five shapes are rectangular, delta, double-delta, trapezoidal, and elliptical fins with a similar length of 6m. The five shapes also show a similar nonlinear trend, with an initial stiffness response. The elliptical and rectangular fins perform the highest capacity at close range. The double delta and the trapezoidal fins provide lower capacity at the same displacement. The rectangular fin provides the highest capacity at approximately 1,864 kN, followed by the elliptical fin at 1,771kN due to the uniform fin along the length of the shaft, which reduces the mobilized soil resistance. The delta, double delta, and trapezoidal fins provide capacities of 1,771, 1,735, and 1,750, respectively. The delta, trapezoidal, and double-delta fins give lower capacities of 1,771.28, 1,750.00, and 1,735.10 kN, which are 6.6%, 7.7%, and 8.5% lower than the rectangular fin. The double-delta and the trapezoidal fin provide similar capacity, which is around 7.68 % to 8.47% lower than the rectangular fin. The results revealed that the shape of the fin has a significant effect on the holding capacity of the torpedo anchor. This helps the researcher in the design of a torpedo anchor in terms of free fall and penetration into the seabed. Fig. 13 represents the ultimate holding capacity for the five different fin shapes. The rectangular fin recorded the greatest capacity, followed by the elliptical fin, as mentioned earlier. The shapes are split into two groups: full-width shapes along the length of the anchor and tapered fin shapes. The difference between the highest and the lowest fin shape anchor is around 8.5%, which is lower than the influence of the length of the width. Overall, the rectangular shape is the most efficient shape. The fin shape influences how the anchor behaves during fall and penetration into the seabed. Knowing the cost and capacity of each shape helps designers balance installation performance against holding capacity when choosing a fin geometry.

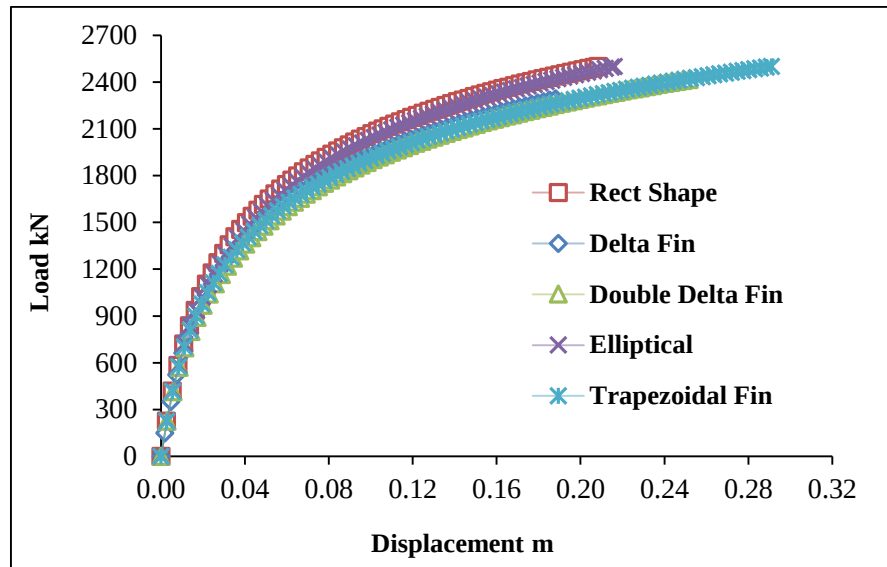


Fig. 12 Load-displacement curves for the effect of fin shape on the holding capacity of anchor model

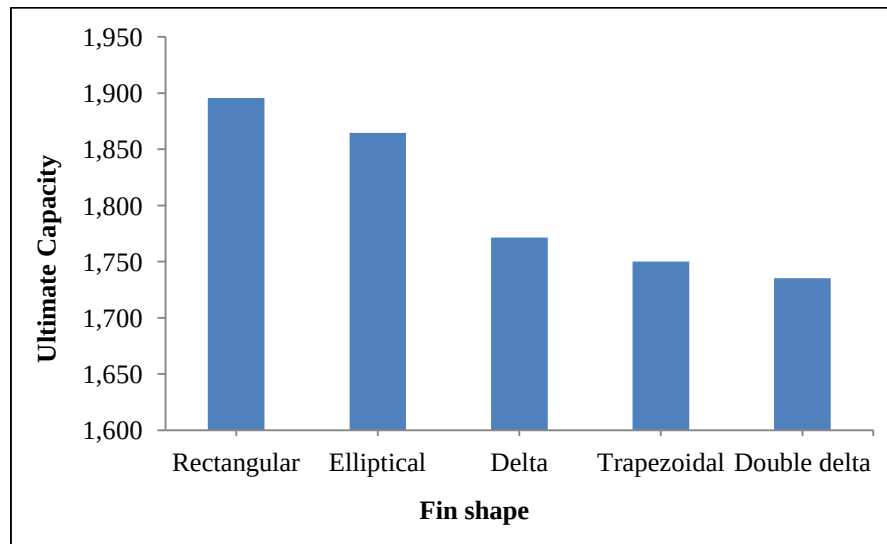


Fig. 13 The ultimate capacity for the anchor of the fin shape: rectangular, delta, double-delta, trapezoidal, and elliptical

Fig. 12 shows the deformation diagram of all anchor model configurations obtained from PLAXIS 3D. The red zone represents the highest displacement, which occurs at the load application point at the top of the shaft anchor. The deformation gradually decreases with increasing depth, and it becomes minimum at the anchor nose. The point of rotation roughly occurs at 8.78 m from the anchor's top for all fin configurations. This soil-anchor interaction analysis helps in understanding the real-life deformation behavior of the torpedo anchor.

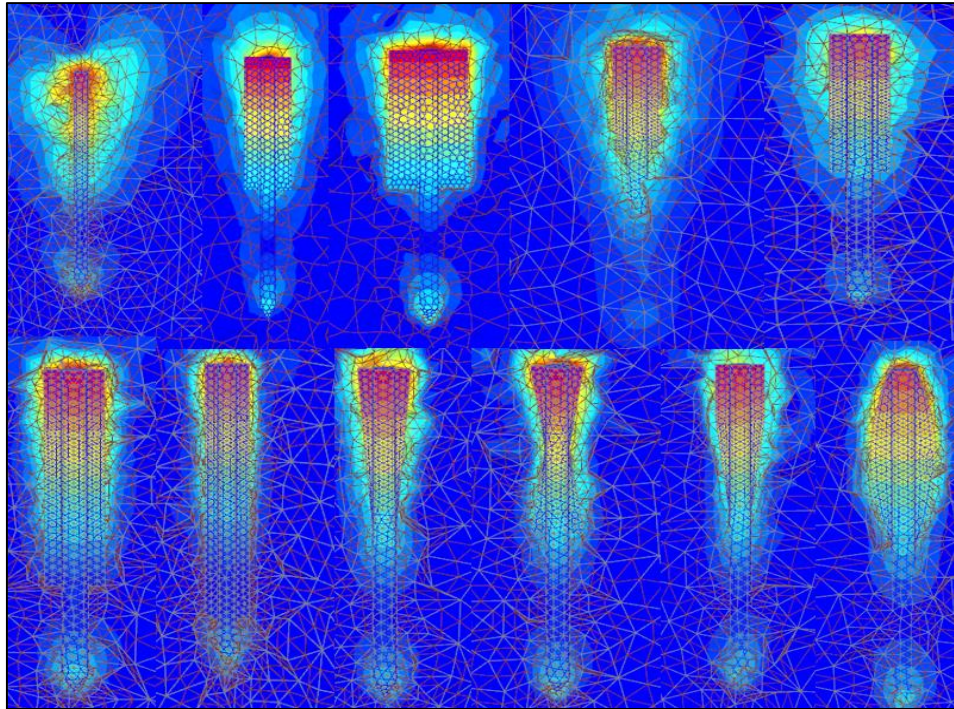


Fig. 12 Deformation behaviour for all fin configurations obtained from PLAXIS 3D

VALIDATION

This work referred to the field test on a finless torpedo anchor of 12m length and 0.762 m diameter penetrated into a seabed at a depth of 20 m (Medeiros 2002). The field test was conducted in the Campos, Brazil area, with a capacity of 1400 kN. The field test was a free fall from a water depth of 1400 m, penetrating 8 m into normally consolidated clay, with a mass weight of 240 kN. The similar parameters of the field test were modelled using the finite element tool PLAXIS 3D. The percentage difference between the field and numerical tests was about 2.14%; therefore, the PLAXIS 3D model of the anchor is valid, and Fig. 8 shows the dashed lines for the 1400 kN field test.

CONCLUSION

This work numerically examined the influence of fin length, width, and shape on the holding capacity of a torpedo anchor in clay soil using the three-dimensional tool PLAXIS 3D. The modified cam-clay constitutive model was used to model the anchors and capture the nonlinear behaviour of normally consolidated clay. The ultimate capacity of the torpedo anchor model was determined from the load-displacement curve at a displacement of 10% of the anchor diameter. The normalized capacity relationship was generated to compare all anchor model configurations. The main conclusions are:

1. The capacity of the anchor model increases significantly with adding fins. All simulated configurations provide greater resistance than the finless anchor, with increases of about 27% to 92%.
2. The effect of length plays a major role in the holding capacity of the anchor model. The holding capacity has a linear relation with the length of the fin. The normalized capacity for $L/3$ and $0.9 L$ anchors is 1.15 and 1.77, respectively. The $0.9 L$ fin anchor recorded the highest holding capacity.
3. Three fin widths were examined: $0.6d$, d , and $1.5d$ and the normalized capacities were 1.39, 1.59 and 1.92, respectively. The highest holding capacity was recorded for the $1.5d$ due to the large resistance area of the fin width.
4. Five shapes of fins were inclined in this study, namely rectangular, delta, double delta, trapezoidal, and elliptical. The rectangular fin provides the highest holding capacity, followed by the elliptical fin with a 1.65% difference.
5. The holding capacity of a torpedo anchor mainly increases due to the interaction between fins and the soil. The holding capacity is an important key for designing the torpedo anchor; therefore, selecting the optimal configuration is highly necessary. The effect of these configurations on the depth of penetration into the seabed and the freefall of the anchor is further recommended.

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Data availability

Data used in this research is available upon request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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