Effect of fins on the pull-out response of model torpedo anchor embedded in soft clay

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1 Introduction

Soft clay is a common seabed material in deep water environments and poses geotechnical difficulties because of its low shear strength. Torpedo anchors behavior in soft clay is still to be investigated. Torpedo anchors provide a less complicated installation procedure and significant holding power. Torpedo anchors are used in deep water regions [1]. The loading angle and anchor aspect ratio influences its centre of rotation and uplift displacement [2]. Properly installed torpedo anchor, achieves up to five times its weight in vertical holding capacity when the CG is located at 0.44 times the length of anchor from its tip [3]. Extreme environmental forces such as strong storms play a vital role in the response of torpedo anchors during installation and pull-out. [4] studied the torpedo piles behavior during installation and pull-out through 1:30 scale model tests in normally consolidated beds of kaolinite clay.

The design methodology of the torpedo anchor mainly depends on its frictional resistance, overbearing resistance, fin geometry and anchor embedment behaviour [2]. The irregular cyclic loading due to wind and wave results in significant rotation in the anchor [5]. A nonlinear finite element approach would provide reasonable performance under the dynamic loads [3]. Using FEM simulations, the anchor penetration, pore pressure generation, stresses and load predictions can be assessed reasonably [6]. The numerical models which account large deformations can provide accurate design approach of torpedo anchors [7]. The free fall velocity, weight and geometry of torpedo pile in different soils is still to be researched [8]. The anchor geometry and energy requirements before installation in the field are still required to be analysed numerically [9]. This paper aims to explore the pull-out load-displacement of torpedo anchors in soft clay with fins under controlled laboratory conditions with a miniature model of a torpedo anchor (1:40 scale, 42.5 cm in length, 2.67 cm diameter) tested in a 1 m diameter and 1 m deep circular tank containing soft clay bed. This paper presents how fin geometry (finless, 2-fin, 3-fin, and 4-fin) and pull-out angles 30°, 45°, 75°, 90° affect the performance of the anchor.

2 Experimental investigation

2.1 Soil

Clay soil was collected from Odalarevu, near Amalapuram, Andhra Pradesh, East Coast of India. The percentage fines present in the soil is 67%, liquid limit is 74% and plastic limit is 33%. A circular test tank made up of steel is used in the present study. The diameter and depth of tank are 1.0 m and 1.0 m respectively. Clay bed was prepared in a test tank at its soft consistency (consistency index, $I_C = 0.49$) with an average undrained cohesion of 10 kPa. Figure 1 shows the preparation of soft clay, model torpedo anchors, and test bed in the tank.

2.2 Model torpedo anchors and test set up

The models were fabricated using a model to prototype ratio (scale) of 1:40. Model torpedo anchors were made up of mild steel of diameter 2.67 cm, length 42.5 cm and varying fin configuration such as finless, two-fin, three-fin and four-fin.

(a) (b) (c)

Figure 1. (a) Soft clay preparation, (b) model torpedo anchor, and (c) test tank with clay bed.

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The pad eye of the torpedo model anchor is connected with an inextensible steel string passing over a smooth pulley. The pulley arrangement is made to the frame of the test tank in a way that the anchor is pulled at required pull-out angles. The top of the anchor is leveled with the bed surface ensuring uniform initial embedment conditions across all the tests. Test is performed at different pullout angles for each fin configuration. The pullout angles maintained are 30°, 45°, 75°, 90° with the horizontal and load is applied gradually using loading plates. The pullout displacement is measured using 100 mm displacement gauge.

3 Discussion of results

Figure 2 depicts the load (N) versus displacement (mm) for torpedo anchor pulled at a 75° angle, with varying fin configurations. From Figure 2a, it is observed that the horizontal displacement in the direction of pull became nearly constant after 4 mm displacement, while inclined and vertical displacements are increasing gradually. Corresponding to a displacement of 18 mm, the maximum load observed is 350 N. Figure 2b shows the response for 2-fin configuration and at 20 mm displacement the maximum pull-out load of 250 N is observed. From Figure 2c, an ultimate pull-out load of 200 N is observed at 22 mm displacement. Anchor with 4-fin (Figure 2d) pulled at 75° showed an ultimate load of 250 N.

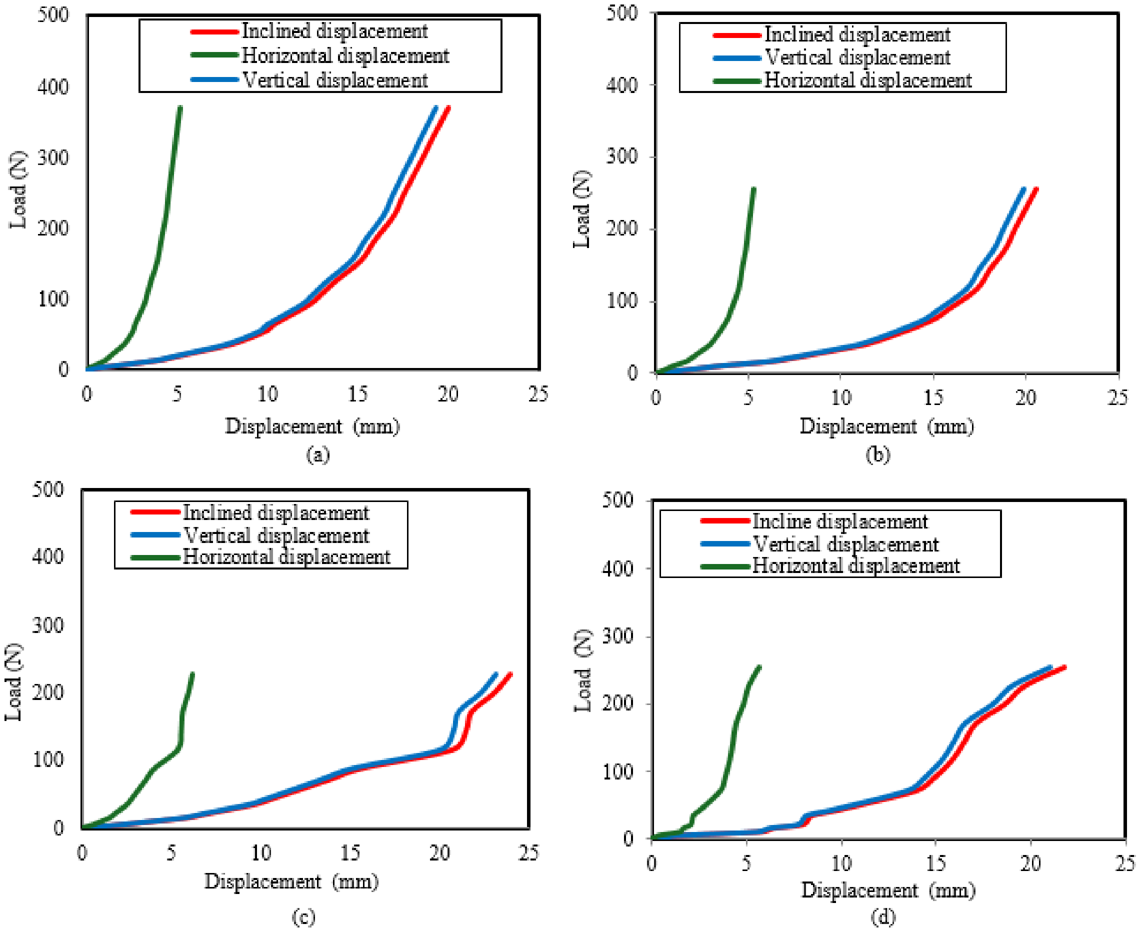

Figure 2. Load vs displacement of model torpedo anchors pulled at 75° (a) finless, (b) 2-fin, (c) 3-fin and (d) 4-fin.

Figure 3 presents the load-displacement behaviour of finless, 2-fin, 3-fin and 4-fin torpedo anchors pulled at 45o. As the number of fins increases, there is a decrease in displacement corresponding to an assigned load value. Finless anchor showed a maximum load of 300 N, whereas 2-fin, 3-fin and 4-fin showed a maximum load respectively 220 N, 200 N and 190 N. The displacements in the pull-out directions corresponding to maximum load are varying from 14 mm to 22 mm. The model torpedo anchors pulled at 300 angle also revealed that the displacement in the pull-out direction (inclined) increases steadily up to 20 mm and corresponding maximum loads observed are 300 N in case of finless, 250 N in 2-fin case, 250 N in 3-fin case and 280 N in 4-fin case. In case of anchors pulled at 90o (Vertically), it is observed that the load increases steadily in the finless torpedo reaching around 402 N, 2-fin and 3-fin configurations resist maximum load of 310 N and 282 N respectively, and the 4-fin anchor showed the maximum load of approximately 254 N. The displacement is increasing in 4-fin case compared to other finless and 3 fin for the same load. The 3-fin configured torpedo showed high pull-out capacity. It may be attributed to mobilization of shear resistance, during pull-out condition. The reduction in pull-out capacity in the 4-fin configured torpedo is due to disturbance of soil surrounded between the fins. At 18 mm displacement the load taken by 2-fin and 4-fin torpedo is 57.9% and 39.5%, respectively more compared to the finless case, while the load in the 3-fin torpedo is 26.3% less.

The load-displacement results obtained from the laboratory tests are further analysed in the form of P/y and y/D, where P is the load (N), D is the diameter of torpedo anchor in mm and y is displacement in mm. The equations 1-4 presented show the P/y and y/D relationships for torpedo anchors of finless, 2-fin, 3-fin and 4-fin respectively and pulled at 90° with horizontal. All these equations are showing regression coefficient as above 0.95. These equations can be utilized to predict the pull-out load in N, for the known values of displacement in mm and diameter of the torpedo anchor in mm.

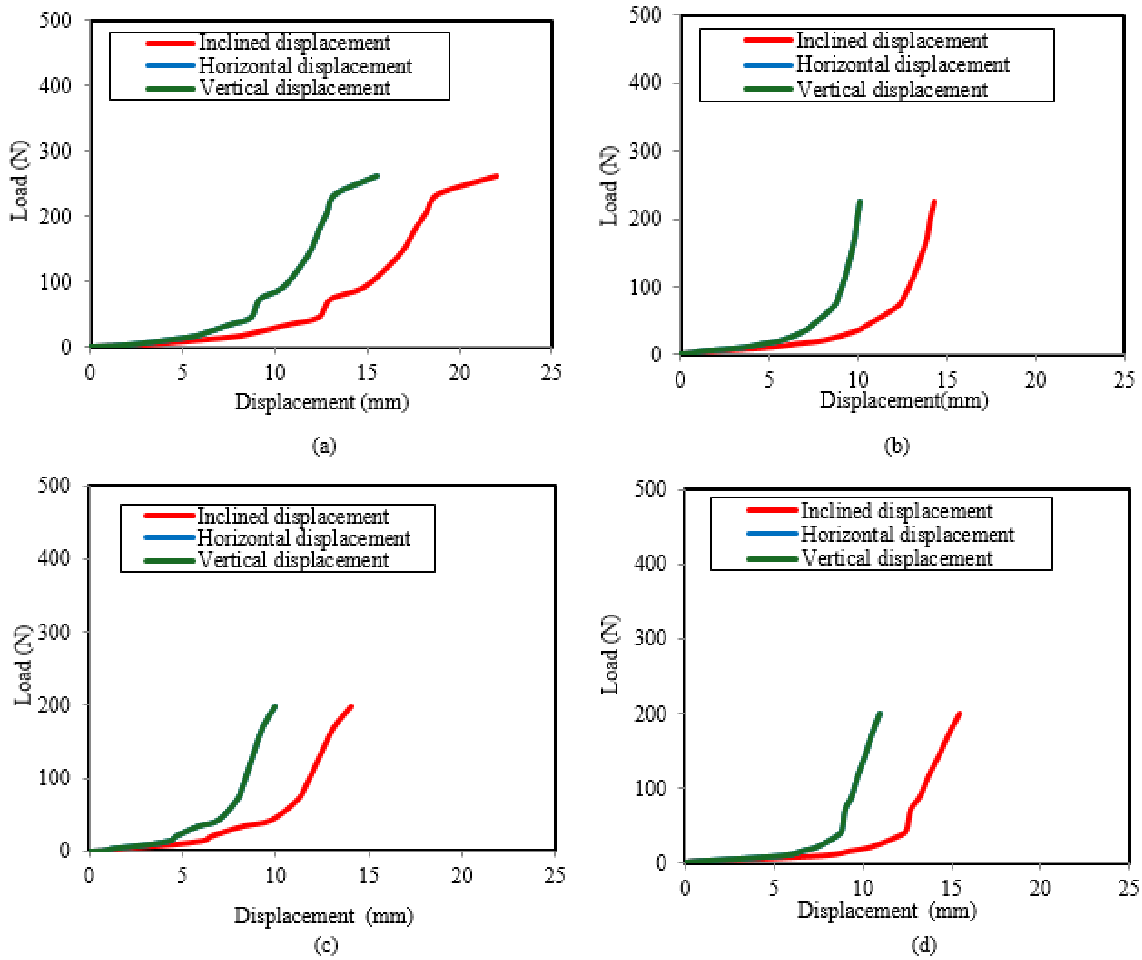

Figure 3. Load - displacement of model torpedo anchors pulled at 45° (a) finless, (b) 2-fin, (c) 3-fin and (d) 4-fin.

$$\frac{P}{y} = 356.4\left(\frac{y}{D}\right)^4 - 412.8\left(\frac{y}{D}\right)^3 + 162.5\left(\frac{y}{D}\right)^2 - 18.14\left(\frac{y}{D}\right) + 2.09 \quad (1)$$

$$\frac{P}{y} = 42.44\left(\frac{y}{D}\right)^4 - 7.41\left(\frac{y}{D}\right)^3 + 73.14\left(\frac{y}{D}\right)^2 - 15.09\left(\frac{y}{D}\right) + 2.77 \quad (2)$$

$$\frac{P}{y} = 42.60\left(\frac{y}{D}\right)^4 + 12.44\left(\frac{y}{D}\right)^3 + 13.73\left(\frac{y}{D}\right)^2 - 17.90\left(\frac{y}{D}\right) + 6.51 \quad (3)$$

$$\frac{P}{y} = 240.3\left(\frac{y}{D}\right)^4 - 333.9\left(\frac{y}{D}\right)^3 + 171.0\left(\frac{y}{D}\right)^2 - 33.54\left(\frac{y}{D}\right) + 3.7 \quad (4)$$

4 Conclusion

This experimental study investigated the pull-out load–displacement behavior of scaled down torpedo anchors embedded in soft clay, with emphasis on the influence of fin configuration and pull-out angle. Four fin geometries (finless, 2-fin, 3-fin, and 4-fin) and four pull-out inclinations (30°, 45°, 75°, and 90°) were examined through controlled laboratory testing. The results provide critical insights into how fin count and pull-out angle affect the anchor's holding capacity, displacement characteristics.

Between the 90^0 to 75^0 pull-out angles, the finless torpedo has more holding capacity by confining displacement and as number of fins increased, the pull-out capacity or holding capacity decreased but displacement is increased. Between

45^0 to 30^0 pull-out angles, the increased number of fins resulted in decreased holding capacity as well as displacement. However, at 90° and 75°, finless anchors showed more load compared to finned anchors, possibly due to the less soil disturbance. High pull-out angles (75° and 90°) generally allow higher load resistance for finless and 2-fin anchors, while 30° and 45° angles favour the finned anchors (3-fin and 4-fin) in terms of holding capacity due to enhanced lateral resistance.

The 2-fin configuration performed well in terms of overall stability, especially at intermediate and high pull-out angles (45° and 75°), offering a better balance between load carrying capacity and displacement. The 3-fin anchor configuration emerged as a highly effective design, particularly under vertical pull-out (90°), delivering maximum pull-out loads and a controlled displacement profile. This configuration benefits from improved soil-anchor interaction while minimizing frontal resistance, which allows for deeper penetration and higher resistance without premature failure. The results discussed are preliminary ones and additional tests will be conducted to further support the conclusions.

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