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Load-Displacement Behavior Of Torpedo Anchor Subjected To Pullout Load In Soft Clay

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Abstract*:* Torpedo anchors are recent foundation systems used to secure offshore structures like oil and gas platforms. This study explored how well these anchors hold in soft clay seabed, focusing on how their fin configuration and the angle at which they are pulled affect their load carrying capacity. Experiments were conducted in the laboratory test tank using a small-scale torpedo anchor model (1:40 scale, 42.5 cm long, 2.6 cm diameter) placed in a 1m diameter and 1m deep tank filled with the soft clay. The clay properties were tested like strength and water content to prepare a test bed in the tank. The model anchor was embedded in a test tank in a way that its top is just at the clay bed surface. The model torpedo is pulled with different pullout angles to see its displacement under applied loads. The study also looked at how different fin configurations like Finless, 2-Fins, 3-Fins and 4-Fins attachments influence the load carrying capacity of torpedo. Results revealed that the fin configured torpedo anchors had enhanced performance in terms of load carrying capacity due to mobilization of shear resistance of surrounded clay soil. The angle at which the anchor pulled out also influenced the holding capacity. Some of the pullout angles showed low holding capacity due to lack of sufficient passive resistance from the soil. These findings would help engineers to understand the behavior of model torpedo and further it provides insights to plan for field testing as well as development of design methodologies to estimate the load carrying capacity. By increasing fin configurations and understanding pullout angles, anchors can work more effectively in soft clay, making offshore platforms safer and more cost-effective in terms of installation.

Index Terms – Torpedo anchors, soft clay, fin configuration, pullout angle, pullout load.

1. INTRODUCTION

Torpedo Anchor was first created by a Brazilian oil painting company during the 1990s, torpedo anchors are heavy pipes, generally several meters long, full of concrete or scrap material. They have a sharp point for simple seabed penetration and generally have fins for stability. Its installation is simple, they are being lowered from a boat, picking up speed to penetrate up to 8 to 22 m in the seabed. This installation system eliminates technical outfit, reducing time and cost relative to conventional anchors. They depend upon soil- anchor interaction to alleviate the loads.

Soft clay is a common seabed material in deepwater environments and poses special geotechnical difficulties because it has low shear strength and is susceptible to remolding under load. These characteristics can have important implications for the performance of torpedo anchors, especially in their pullout load-deflection behavior, which is an important measure of their capacity to resist forces without losing positional stability. The design of the anchor, the fin configuration, and the loading angle are some of the variables that affect torpedo anchor pullout capability. Fins maximize the anchor-soil contact area, promoting lateral resistance and mobilizing more soil strength, while the loading angle influences the shear zones of the soil and anchor stability. Comprehending these interactions in soft clay is critical to maximizing anchor design, safety and durability of moored offshore structures.

Recent studies have expanded the knowledge base on torpedo anchor behavior and the performance of related deepwater anchoring systems. Chang et al. (2024) examined torpedo anchors for floating offshore wind turbines (FOWTs), comparing them to driven piles, suction caissons, and drag anchors. Using CFD simulations optimized hydrodynamic stability and center of gravity (CG) positioning, showing that the T-98 torpedo anchor can achieve up to five times its weight in vertical holding capacity when the CG is located at 0.44 L from the tip. Hirai (2023) proposed a new bearing capacity equation for suction anchors with embedment lengths greater than their diameter in sand, identifying distinct failure surfaces for various loading types. Cheng et al. (2022) used nonlinear finite element (FE) method to find tripod suction anchors under environmental and seismic loads while Feng et al. (2022) modeled suction anchor behavior under vertical, horizontal, and moment loads in silt-over-clay deposits, validating results with test data and performing parametric studies on soil layering and embedment ratios. Other research has addressed cyclic and dynamic loading effects. Luo et al. (2020) found that irregular cyclic loads from wind and waves cause significant rotational accumulation in suction anchors. Wang et al. (2018) conducted 240 laboratory tests on 11 torpedo anchor designs in cohesive soils, developing an empirical formula incorporating embedment depth, geometry, weight, and soil properties, and highlighting the dominant role of fin design. Hossain et al. (2015) studied torpedo anchors in calcareous silt, revealing the influence of brittle soil behavior on load–displacement response. Kim et al. (2015) used ABAQUS simulations to investigate anchor installation in clay, focusing on penetration stresses, pore pressure, and post-installation performance. Earlier studies also contribute valuable insights. Hossain et al. (2014) compared dynamically penetrating anchors (DPAs) in soft clay and silt, identifying differences in embedment and holding strength. Kim et al. (2014) examined dynamic penetration in calcareous silt using FE modeling validated with experiments. Sagrilo et al. (2011) analyzed soil strength, load inclination, and fin geometry effects, noting that accurate FE models must consider large deformations. Audibert et al. (2006) conducted laboratory and field tests on torpedo piles across various soil types, addressing scale effects and installation energy dissipation. Brandao et al. (2006) documented installation process is used for FPSO P-50 anchor, and Araujo et al. (2004) reported long-term field performance of high-holding power torpedo piles, confirming their efficiency and feasibility in deepwater. De Araujo et al. (2004) described the installation and performance of T-98 anchor, achieving holding capacities of 7500 kN. Early conceptual work by Medeiros (2001) introduced the dynamic installation of anchor concept and outlined cost and time benefits.

The present study builds on these findings by experimentally evaluating a scaled-down torpedo anchor model (1:40 scale, 42.5 cm length, 2.6 cm diameter) in a 1.0 m diameter soft clay tank. Fin configurations (Finless, 2-Fins, 3-Fins, 4-Fins) and fin angles (30°, 45°, 75°, 90°) are tested, with additional measurements of undrained shear strength and water content to replicate actual seabed conditions. The aim is to quantify how fin geometry and soil parameters affect pullout capacity, contributing to improved design practices for deepwater mooring applications.

2. PREPARATION OF MODEL TESTS

2.1 SOIL

Collected the clay soil sample from the Peddavagu near Janagoan in Telangana and pulverized them into suitable fractions using wooden mallet and stored in the airtight bags. The clay soil was tested for basic properties such as Liquid limit IS2720 (Part 5), Plastic limit IS 2720 (Part 5), Sieve analysis IS 2720 (Part 4) and Vane shear test IS 2720 (Part 30). The testing was conducted in the laboratory under controlled conditions and as per the procedures mentioned in the Indian Standards. The basic properties of clay soil are presented in Table.1.

Table.1 Basic properties of soil

S. No	Soil Property	Value
1.	Specific gravity	2.7
2.	**Grain size analysis**	
	• % Fine fraction (silt and clay)	67.0
	• % Sand	31.0
	• % Gravel	2.0
3.	**Atterberg Limits**	
	• Liquid Limit (%)	74
	• Plastic Limit (%)	33
	• Plasticity Index (PI)	41
4.	Soil Classification	**CH**

2.2 Test Tank Setup and Clay Bed Preparation:

A circular test tank made up of steel is used in the present study. The diameter of the tank is 1.0 m and its depth is 1.0 m. The soil sample pulverized with wooden mallet is spread to air dry and soil is mixed with water to maintain a consistency Index of (0.25-0.5) for soft clay firmness and maintaining the moisture content by covering the soil with the gunny bags.Fig.1 shows the test tank setup.

$$I_c=((W_L-W_n)/(W_L-W_P))=\left(\frac{(74-54)}{(74-33)}\right)=0.48=48\%$$

The crushed soil is kept for air dry and mixed with water for maintaining soft consistency. The test tank was filled up with clay soil in layers and tamped with wooden mallet ensuring no air voids and allow the soil to mature for a period of 48 hours.

2.3 Anchor Model Fabrication:

In this laboratory study, the 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, 2-Fins, 3-Fins and 4-Fins. The fabrication was done based on 1:40 scale torpedo (Brandao et al., 2006). Fig 2 shows the fabricated model for laboratory study.

2.4 Anchor Placement and Load application:

Model Torpedo anchors were embedded into clay bed prepared in the test tank. The top of the anchor is leveled with the bed surface ensuring uniform initial embedding conditions across all the tests. Test is performed at different pullout angles for each fin configuration at a time. The pullout angle was maintained as 30^0, 45^0, 75^0 and 90^0. Load is applied gradually using loading plates.

Fig.1 Test tank set up

Fig.2 Fabricated models

3. RESULTS AND DISCUSSION

Figs. 3 to 12 show the Load vs. Displacement for different fin configuration pulled at 30 °, 45 °, 75 °, 90 °. Finless torpedo is resisting more pullout load when compared to all other fin configuration. Between 90^{0}to 75^0 pullout angles, finless torpedo is resisting more pullout load by confining displacement and as the fins are increasing the pullout capacity is decreasing and displacement is increasing. Between 45^0 to 30^0 pullout angles, as the number of fins increases the pullout load as well as displacements are decreasing.

Fig.13 to 16 show Load vs. Displacement curves at 5% D, 10% D and 15% D (where D is the diameter of torpedo anchor) for different pullout angles and different fin configuration. High pullout angles (75°–90°) generally maximize load resistance across torpedo anchor configurations, with the Finless design achieving the highest load (14 N at 75°, 15% D). The 45° angle consistently showing the lowest load capacity at 5% D. The 4-Fins torpedo performing well at both 30° and 75°, suggesting fin configuration influences optimal angles.

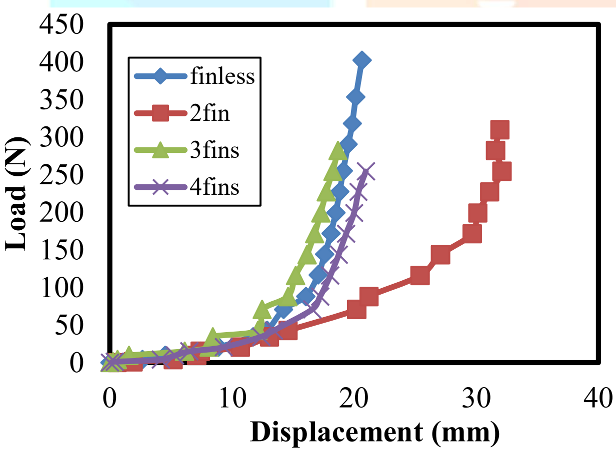

Fig. 3 Load vs. Displacement pulled at 90 º

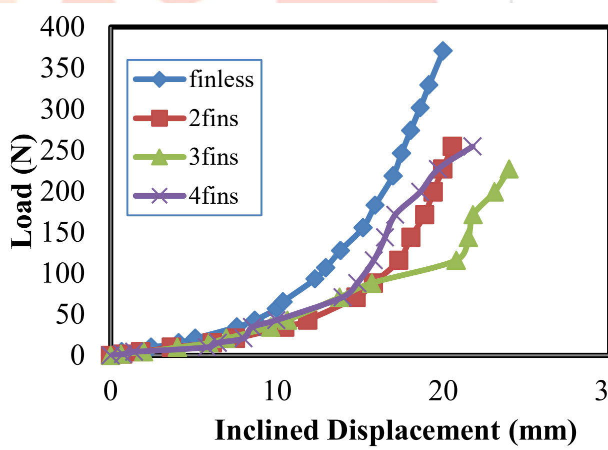

Fig.4 Load vs. Inclined displacement pulled at 75^0

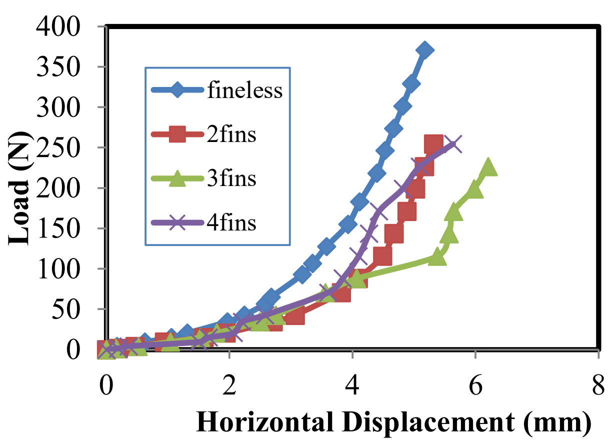

Fig. 5 Load vs. Horizontal dispalcement pulled at 75^0

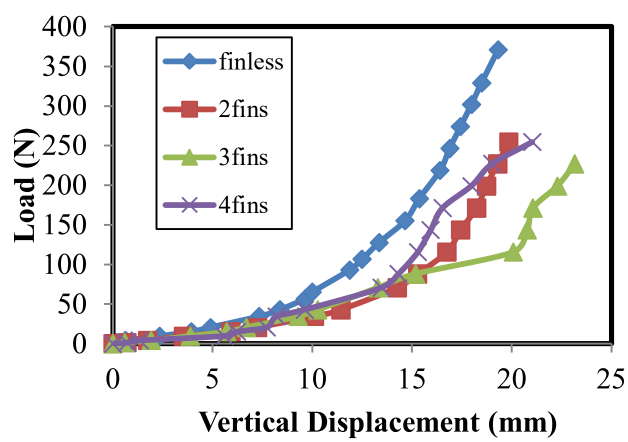

Fig. 6 Load vs. Vertical displacement pulled at 75^0

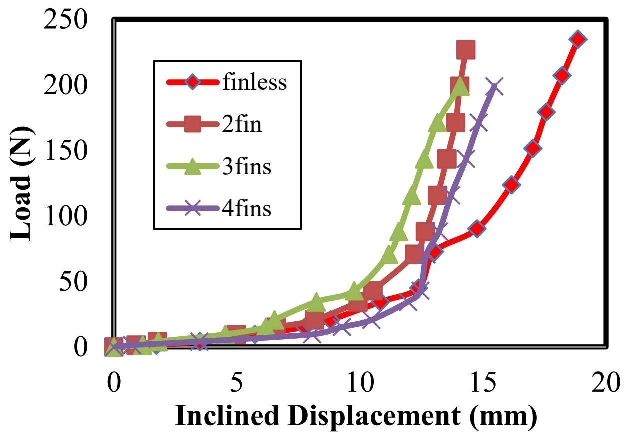

Fig.7 Load vs. Inclined displacement pulled at 45⁰

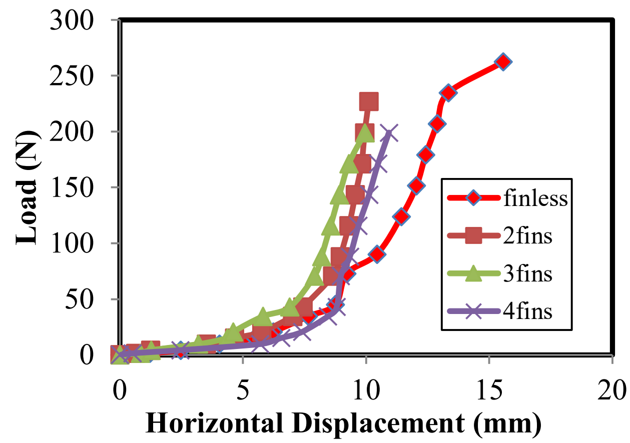

Fig.8 Load vs. Horizontal displacement pulled at 45⁰

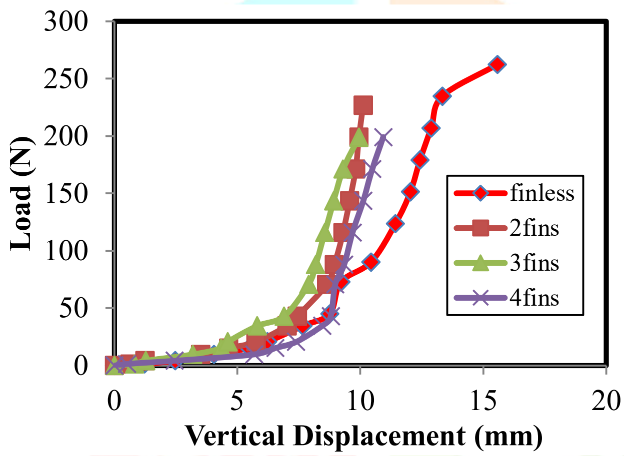

Fig.9 Load vs. Vertical Displacement pulled at 45⁰

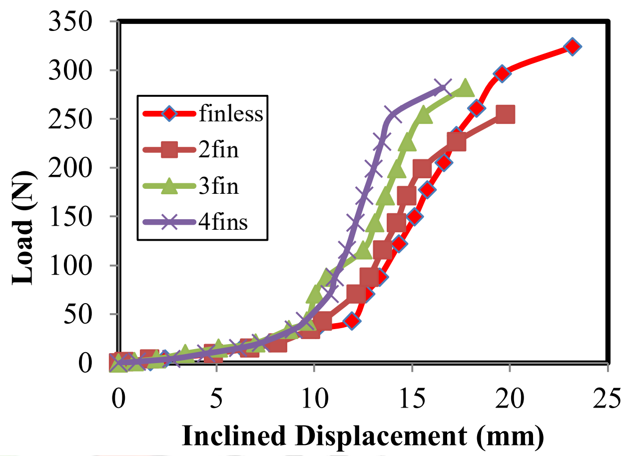

Fig.10 Load vs. Inclined displacement pulled at 30⁰

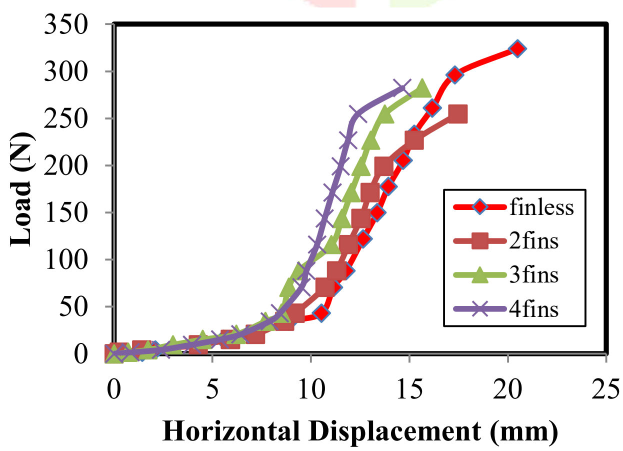

Fig.11 Load vs. Horizontal displacement pulled at 30⁰

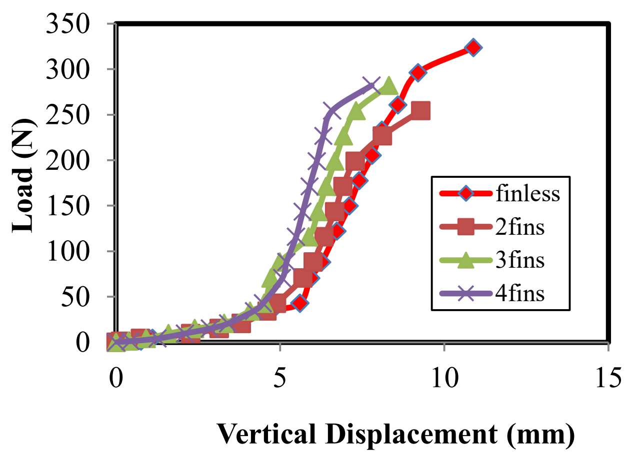

Fig.12 Load vs. Vertical displacement pulled at 30⁰

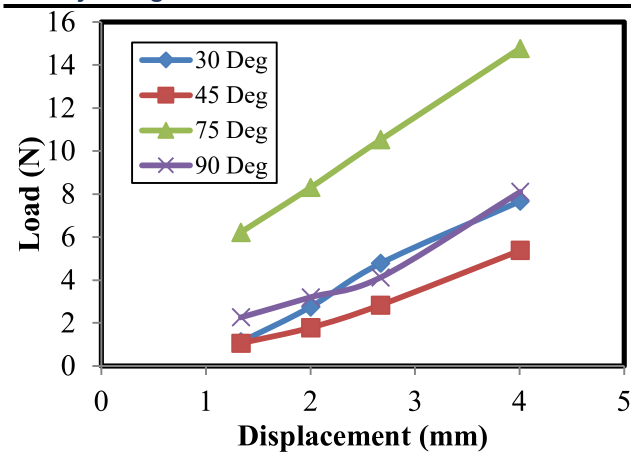

Fig.13 Load – Displacement curves at 5% D, 10% D and 15% D of Finless Torpedo

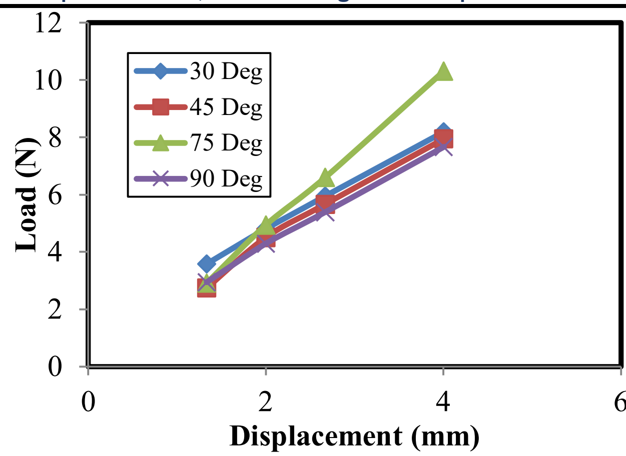

Fig.14 Load – Displacement curves at 5% D, 10% D and 15% D of 2-Fins Torpedo

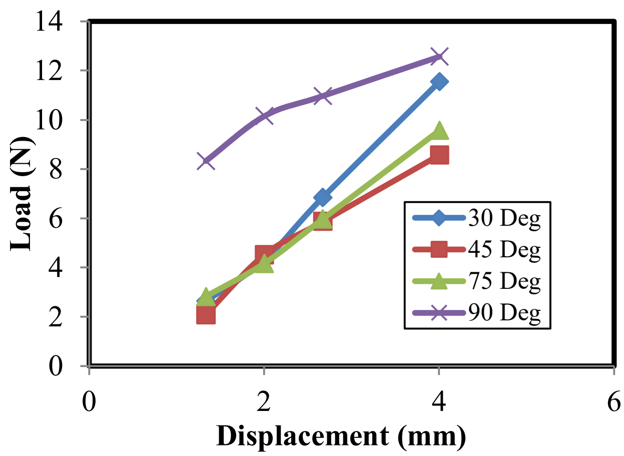

Fig.15 Load – Displacement curves at 5%D, 10% D and 15% D of 3-Fins Torpedo

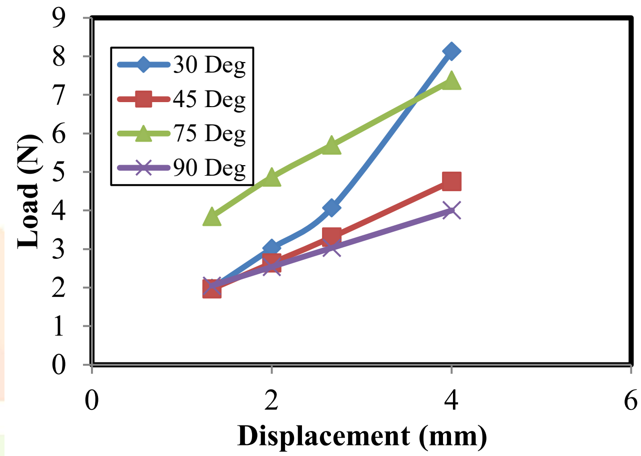

Fig.16 Load – Displacement curves at 5% D, 10% D and 15% D of 4-Fins Torpedo

Table.2 shows the summary of all the Load-Deflection observations and percentage comparison of Pullout load for different fin configuration and different pullout angles.

Table.2 Summary of Load–Displacement Observations for Different Fin Configurations and Pullout Angles

Pullout Angle	Fin Configuration	Inclined Load (N)	% Reduction in load in comparison of Finless torpedo	Displacement (mm)
90°	Finless	402	—	20.63
	2-Fins	337	↓ 16%	31.93
	3-Fins	280	↓ 30%	18.67
	4-Fins	254	↓ 36%	20.95
75°	Finless	370	—	20
	2-Fins	254	↓ 31%	20.55
	3-Fins	226	↓ 38%	23.98
	4-Fins	254	↓ 31%	21.77
45°	Finless	262	—	22
	2-Fins	226	↓ 13%	14.3
	3-Fins	200	↓ 23%	14.07
	4-Fins	200	↓ 23%	15.46
30°	Finless	323	—	23
	2-Fins	254	↓ 21%	19.78
	3-Fins	282	↓ 12%	17.72
	4-Fins	282	↓12%	16.58

4. CONCLUSION

- Between 90^0 to 75^0 pullout angles, the finless torpedo has more holding capacity by confining displacement and as number of fins increased, the pullout capacity or holding capacity decreased but displacement is increased.
- Between 45^0 to 30^0 pullout angles, the increased number of fins, resulted in decreased holding capacity as well as displacement.
- Torpedo with Fins enhanced the load carrying capacity at lower pullout angles (30° and 45°) due to increased soil-anchor interaction and shear resistance offered by the surrounded soil. However, at 90° and 75°, finless anchors showed more load compared to finned anchors, possibly due to the less soil disturbance.
- High pullout 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 finless torpedo anchor exhibited the highest load-carrying capacity at a 90° pullout angle. The finless anchor's load-displacement behavior showed a gradual increase in the displacement before failure, highlighting its reliance on soil friction rather than enhanced shear resistance.
- The 2-fin configuration performed well in terms of overall stability, especially at intermediate and high pullout 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 pullout (90°), delivering maximum pullout loads and a controlled displacement profile. This configuration benefit from improved soil-anchor interaction while minimizing frontal resistance, which allows for deeper penetration and higher resistance without premature failure.
- The 4-fin configuration demonstrated the more resistance under shallow pullout angles (notably at 30°), confirming that the additional fin area provides increased soil confinement and lateral resistance. However, under higher pullout angles, particularly at 75° and 90°, the performance slightly declined, likely due to increased disturbance of soil around the torpedo anchor.

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