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Experimental Investigation on the Axial Pullout Capacity of Helical Piles in Loose Sand

Ashni M¹, Jenisha Varshini J², B. J. Pradesh³, Jebin J⁴, Kannitha Micheal J⁵

¹Assistant professor, Stella Mary's College of Engineering

^{2,3,4,5}IV Year Civil Department, Stella Mary's College of Engineering

Abstract— Helical piles provide a rapidly installable deep-foundation solution for structures subjected to uplift and axial actions. This paper presents a laboratory investigation of the axial pullout response of single-, double-, and triple-helix model piles embedded in loose sand. The model piles used a 15 mm steel shaft, 75 mm diameter helices, 2 mm helix thickness, 15 mm pitch, and 700 mm total length. Pullout tests were conducted at embedment ratios $H/D = 2.5$ and 4.0 using a tank-and-pulley loading system with dial-gauge displacement measurement. The measured ultimate pullout capacities were 5.67, 7.56, and 9.45 kg at $H/D = 2.5$ and 12.72, 16.62, and 23.69 kg at $H/D = 4$ for piles with one, two, and three helices, respectively. The test results show a consistent increase in uplift resistance with both helix number and embedment ratio, while the load-displacement curves indicate progressively delayed and reduced deformation before failure as the number of helices increases. The study demonstrates the combined importance of helix configuration and embedment in the pullout performance of model helical piles in loose cohesionless soil.

Index Terms— axial pullout, embedment ratio, helical pile, loose sand, model test, uplift capacity

I. Introduction

Deep foundations and anchors are used when structural actions must be transferred through weak near-surface deposits to more competent soil or when significant tensile resistance is required. Helical piles are especially attractive for uplift applications because one or more steel helices welded to a central shaft mobilize bearing and shear resistance within the surrounding soil. They can be installed quickly, accept load immediately after installation, and are applicable to land and offshore structures subjected to wind, wave, hydrostatic, seismic, and other actions. The pullout response of a multi-helix pile depends on helix geometry, spacing, soil condition, and embedment. When helix spacing is small, the soil enclosed between plates may participate in a cylindrical shear mechanism; at larger spacing, the helices may develop more independent failure surfaces.

Prior experimental and numerical studies have reported that uplift resistance is sensitive to helix arrangement, embedment, installation conditions, and the density or strength of the surrounding soil [2], [4], [5], [7], [8], [12], [13]. In sandy soils, increasing the number or effective area of helices generally increases pullout resistance, while greater embedment provides a larger confining mass and a longer potential failure path. However, model-scale observations remain useful for clarifying how these variables interact under controlled conditions. The present study therefore compares three model helical piles in loose sand at two embedment ratios and examines their load-displacement response and ultimate pullout capacity.

II. Experimental Program

2.1 Soil Characterization and Model Piles

Naturally available reddish-brown sand was collected after removing the vegetated surface layer, air-dried, and characterized in the laboratory. Specific gravity was measured using a pycnometer in accordance with IS 2720 (Part 3/Sec 1) [9], and grain-size distribution was obtained by sieve analysis following IS 2720 (Part 4) [10]. The reported specific gravity was 2.64 and the fineness modulus was 2.91. The gradation data were classified in the source study as well-graded sand. The material was prepared in a loose density state for all axial pullout tests so that the effect of pile geometry and embedment could be compared on a consistent soil bed.

Three solid mild-steel model piles, denoted P1, P2, and P3, were fabricated with one, two, and three helices, respectively. The shaft diameter was 15 mm, helix diameter 75 mm, helix thickness 2 mm, helix pitch 15 mm, and total pile length 700 mm. For the multi-helix piles, the center-to-center spacing between successive helices was 100 mm; the lowest helix was positioned 50 mm above the pile tip. Two embedment ratios, $H/D = 2.5$ and $H/D = 4.0$, were investigated, giving six tests in the loose sand state.

Table 1: Principal Experimental Parameters

Parameter	Value / condition
Soil condition	Loose, well-graded sand
Specific gravity	2.64
Fineness modulus	2.91
Pile shaft diameter	15 mm

Helix diameter / thickness	75 mm / 2 mm
Helix pitch	15 mm
Pile length	700 mm
Helix count	P1: 1; P2: 2; P3: 3
Helix spacing (P2, P3)	100 mm
Embedment ratio, H/D	2.5 and 4.0
Tank size	750 × 1000 × 1000 mm
Dial gauge resolution	0.02 mm

2.2 Test Setup and Loading Procedure

The pullout tests were performed in an iron tank measuring 750 mm × 1000 mm × 1000 mm. A steel wire rope connected the pile head to a load hanger through a two-pulley arrangement. Axial load was increased in equal increments, and vertical pile movement was monitored with a dial gauge. During testing, each load increment was maintained until the reported displacement rate criterion of 0.02 mm/h was reached. Loading continued until the pile was pulled out of the soil bed, and the corresponding load was taken as the ultimate pullout capacity. The source report records one dial gauge for the basic setup and describes averaging two gauges for the H/D = 4 tests; the measured final displacements were then plotted against applied pullout load.



Figure 1. Experimental pullout test tank and pulley loading arrangement.

III. Results and Discussion

3.1 Load-Displacement Response

At H/D = 2.5, P1 showed measurable displacement from a relatively low load level, increasing from 0.15 mm at 1.26 kg to 3.25 mm at 5.04 kg before failure at 5.67 kg. P2 remained essentially stationary through the initial load stages and recorded 0.69 mm at 3.78 kg, 2.10 mm at 6.30 kg, and 4.54 mm at 6.93 kg before failing at 7.56 kg. P3 exhibited the largest pre-mobilization resistance: displacement remained zero through 4.41 kg, then rose from 0.15 mm at 5.04 kg to 5.89 mm at 8.82 kg before failure at 9.45 kg. Thus, adding helices shifted the load-displacement response to higher load levels and increased the load required to initiate appreciable movement.

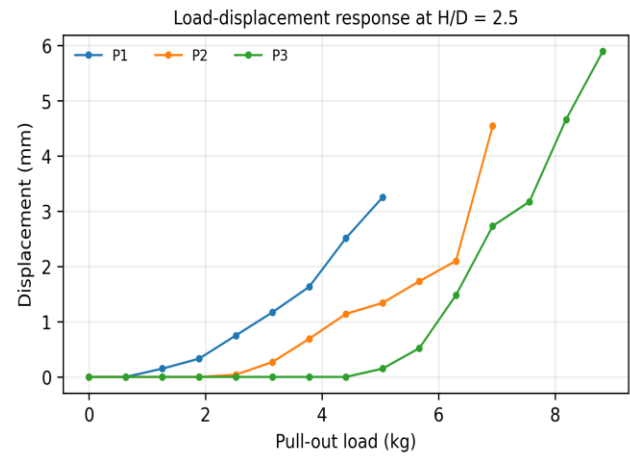


Figure 2. Measured load-displacement response at H/D = 2.5 (failure points omitted because no displacement value was reported at failure).

3.2 Ultimate Capacity and Effect of Helix Number

The ultimate pullout capacities are summarized in Table II. For H/D = 2.5, capacity increased from 5.67 kg for P1 to 7.56 kg for P2 and 9.45 kg for P3. At H/D = 4, the corresponding capacities were 12.72, 16.62, and 23.69 kg. The ranking P3 > P2 > P1 was therefore maintained at both embedment ratios. The trend is consistent with the increased bearing and shear resistance mobilized by additional helix plates. For P2 and P3, the 100 mm helix spacing corresponds to S/D ≈ 1.33; in the conceptual framework discussed in the source report, this relatively close spacing is compatible with interaction of the soil between helices and a cylindrical-type shear mechanism rather than fully independent plate action.

Table 2: Ultimate Pullout Capacity From The Reported Tests

Pile	H/D = 2.5 (kg)	H/D = 4 (kg)
P1	5.67	12.72
P2	7.56	16.62
P3	9.45	23.69

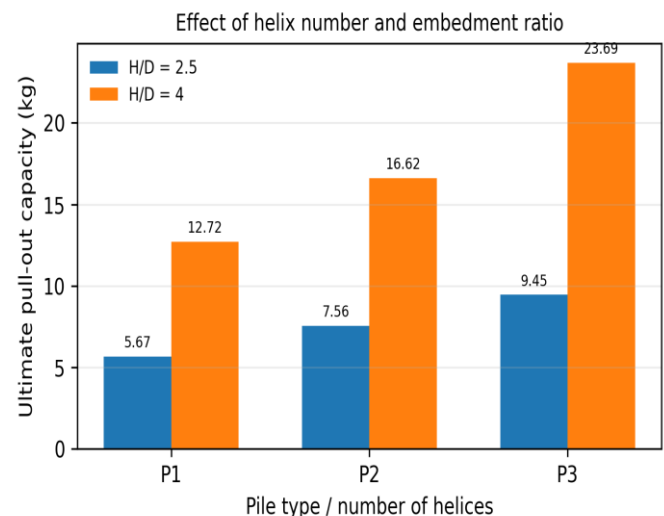


Figure 3. Comparison of ultimate pullout capacity for the three pile configurations and two embedment ratios.

3.3 Effect of Embedment Ratio

Increasing the embedment ratio from 2.5 to 4 substantially enhanced resistance for every pile configuration. Using the tabulated ultimate capacities, the $H/D = 4$ to $H/D = 2.5$ capacity ratios are approximately 2.24 for P1, 2.20 for P2, and 2.51 for P3. This indicates that deeper embedment was at least as influential as adding a helix within the tested range. The combined effect is strongest for P3, which reached 23.69 kg at $H/D = 4$ compared with 5.67 kg for the single-helix pile at $H/D = 2.5$. Greater embedment places the helices beneath a larger overburden and extends the soil mass that must deform or shear during uplift, while additional helices enlarge the pile-soil interaction zone. These mechanisms explain the systematic increase in capacity observed in Fig. 3 and agree with the broad trends reported in earlier studies on screw and helical anchors in cohesionless soils [7], [8], [13].

A data-consistency issue was noted in the source project report: the percentage increases stated in its narrative and conclusion do not numerically match the tabulated ultimate capacities. To avoid combining inconsistent values, the present paper uses the reported capacity tables as the quantitative basis and computes comparative ratios directly from those values. No unreported test points or failure displacements have been introduced.

3.4 Load-Displacement Response at $H/D = 4$

The deeper test series produced the same ordering of response but at substantially larger loads. For P1, displacement increased from 0.28 mm at 1.413 kg to 1.15 mm at 5.654 kg, 4.00 mm at 9.894 kg, and 6.53 mm at 11.308 kg before failure at 12.721 kg. P2 showed negligible displacement through 6.725 kg and only 0.04 mm at 8.135 kg; deformation then increased to 0.73 mm at 10.965 kg, 2.10 mm at 13.795 kg, and 4.54 mm at 15.205 kg before failure at 16.623 kg. The triple-helix pile P3 was still more resistant to initial movement: the reported displacement remained zero through 13.795 kg, then increased from 0.15 mm at 15.205 kg to 2.42 mm at 22.277 kg before failure at 23.691 kg. These observations confirm that the gain in ultimate capacity was accompanied by a shift of the full load-displacement curve toward higher load levels.

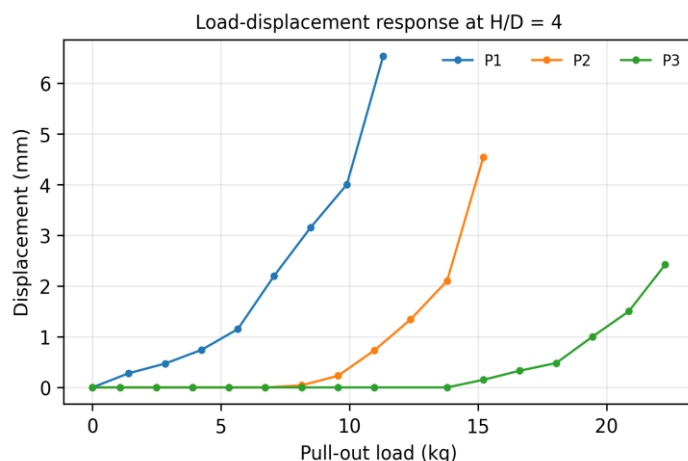


Figure 4. Measured load-displacement response at $H/D = 4$ (failure points omitted because no displacement value was reported at failure).

3.5 Interpretation of Helix Interaction

The source report discusses two idealized uplift mechanisms for multi-helix foundations: individual plate uplift and cylindrical shear uplift. For widely spaced helices, each plate can mobilize a comparatively independent failure surface, whereas at closer spacing the soil enclosed between the upper and lower helices may move as a more continuous cylindrical mass. In the present models, the multi-helix spacing was 100 mm and the helix diameter was 75 mm, giving $S/D \approx 1.33$. This spacing is below the commonly discussed range at which individual plate behavior becomes dominant, so interaction between adjacent helices is expected to be significant. The laboratory data are consistent with that interpretation because P2 and P3 did not simply show earlier deformation at each added plate; instead, their load-displacement curves remained comparatively stiff over a larger loading interval before rapidly approaching failure.

The improvement associated with the third helix becomes more pronounced in the deeper series. At $H/D = 2.5$ the increase from P2 to P3 was 1.89 kg, whereas at $H/D = 4$ the increase was 7.07 kg based on the tabulated capacities. This does not prove a unique failure mechanism, because the tests did not directly map the internal shear surface, but it indicates that helix number and embedment are not independent design variables. A deeper multi-helix arrangement can mobilize a larger and better confined soil mass than a shallow arrangement with the same helix geometry. This interaction is important when interpreting model tests and when selecting helix number for uplift-dominated applications.

3.6 Engineering Implications and Study Limitations

From an engineering standpoint, the test matrix shows two practical trends. First, adding helices is an effective way of increasing uplift resistance when shaft and helix dimensions are unchanged. Second, increasing embedment can yield an even larger gain because the overlying soil contributes additional confinement and resistance to the upward movement of the helix system. The highest capacity was obtained from P3 at $H/D = 4$, while the lowest was obtained from P1 at $H/D = 2.5$; the ratio between these two measured capacities is approximately 4.18. For preliminary selection, this illustrates why both geometry and embedment must be considered together rather than optimizing one parameter in isolation.

The results should nevertheless be interpreted within the limits of the experimental program. Only one loose sand condition, one helix diameter, one shaft diameter, one multi-helix spacing, and two embedment ratios were tested. The number of tests was six, and the source report does not provide statistical repeatability, installation torque histories, in-situ density measurements for each test, or direct observations of the subsurface failure surface. Model-scale boundary and scale effects may also influence the measured response. Consequently, the reported capacities are best used to establish comparative trends within this test configuration rather than as direct prototype design values. A broader program incorporating repeat tests, additional relative densities, larger S/D ratios, installation torque, and image-based observation of soil deformation would provide a stronger basis for design correlations.

IV. Conclusions

Laboratory axial pullout tests on model helical piles in loose sand demonstrated clear effects of both helix number and embedment. With all other model dimensions held constant, increasing the number of helices from one to three raised the ultimate pullout capacity at both $H/D = 2.5$ and $H/D = 4$. The triple-helix pile produced the highest measured capacity in each test series, while the single-helix pile produced the lowest. The load-displacement data at $H/D = 2.5$ further showed that multi-helix piles sustained higher loads before appreciable displacement developed. Increasing the embedment ratio from 2.5 to 4 more than doubled the reported ultimate capacity for each pile type, indicating a strong contribution from soil confinement and the larger mobilized failure zone. Within the limitations of a small-scale loose-sand model, the findings support the use of increased embedment and multiple helices to improve uplift resistance. Further work should examine additional helix spacings, relative densities, installation effects, scale effects, and repeat tests so that the observed trends can be translated more reliably to field design.

For the tested geometry, the results also show that performance should not be described by helix count alone. The effect of adding the third helix was much larger in the $H/D = 4$ series than in the $H/D = 2.5$ series, emphasizing that helix interaction develops within the confining soil mass created by embedment. A design-oriented interpretation should therefore consider helix diameter, spacing ratio, embedment ratio, soil density, and installation process as coupled variables. The laboratory results provide a useful comparative basis for this interaction, but prototype application requires appropriate geotechnical characterization and scale-sensitive design procedures.

Future experimental work should include repeated specimens for statistical confidence, direct measurement of relative density before and after installation, monitoring of installation torque, and transparent observation of the soil failure pattern using a side-view tank or image-correlation technique. Testing S/D values both below and above the transition range discussed in the literature would help distinguish cylindrical and individual-plate mechanisms. Additional tests under denser sand, inclined loading, and cyclic uplift would also extend the relevance of the present findings to offshore and other structures exposed to variable environmental actions.

V. References

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