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Simulating the uplift response of helical piles in sand using a hypoplastic model

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ABSTRACT: Helical piles, also known as screw piles, have emerged as a novel foundation technique for offshore structures. It is due to their potential to enhance uplift capacity and their environmental advantages, including minimal vibration, limited noise, and reduced soil spoil. In many applications, the uplift capacity of helical piles serves as the primary design criterion. This research conducted a numerical study to assess the load-displacement behaviour of single-helix helical piles subjected to uplift loading in dry dense sand using the Hypoplasticity model. Triaxial tests were initially simulated to calibrate and validate the model's parameters and examine its predictive capabilities. Subsequently, the constitutive model was employed to simulate the response of helical piles under tension loading. The load-displacement profiles for helical piles were generated, and the corresponding uplift capacities were obtained. Comparing the numerical results against centrifuge test data revealed that the hypoplastic model provides a realistic representation of helical pile behaviour under loading conditions, highlighting its reliability in predicting the uplift capacity of helical piles.

Keywords: Helical pile; Hypoplasticity; Offshore foundation; Sand; Uplift capacity

1 INTRODUCTION

A helical pile (see Figure 1) is a displacement pile consisting of a steel shaft and helix-shaped plate(s). Helical piles are installed using a hydraulic torque unit at the top of the pile, effectively screwing them into the soil. Compared to conventional piles, helical piles offer environmental benefits (Perko, 2009) and exhibit remarkable strength (Mitsch and Clemence, 1985; Ghaly et al., 1991). Because of these advantages, helical piles have not only been extensively used as a reliable foundation option for various onshore structures but also, in recent years, there has been growing interest in their potential to replace traditional driven piles in offshore applications.

Several research studies have been performed to address the uncertainties regarding the failure mechanism of helical piles under tension loading and to determine their uplift capacity in sand. These investigations were generally performed experimentally in the field (Mitsch and Clemence, 1985; Spagnoli et al., 2015) or in the lab through centrifuge (Tsuha et al., 2007; Al-Baghdadi, 2018; Hao et al., 2019; Davidson et al., 2022) or 1g (Mitsch and Clemence, 1985; Ghaly et al., 1991; Spagnoli et al., 2015; Annicchini et al., 2022) tests. Along with these experimental works, a number of studies have also tried to predict the uplift capacity of helical piles in sand through numerical methods (e.g, Kurian and Shah, 2009; Gavin et al., 2014; Al-Baghdadi, 2018; Cerfontaine et al., 2021).

Figure 1. A 3D sketch of a single-helix helical pile.

Helical piles are subjected to complex stress distributions and loading conditions. The majority of numerical studies on helical piles have utilised simple elasto-plastic models, which tend to simplify the behaviour of sand under shear loading. While this simplification allows for a more straightforward analysis, it often neglects the intricate aspects of soil mechanics, potentially leading to less reliable designs. Hypoplastic models provide a robust framework for capturing soil responses in realistic loading scenarios, thereby enabling more precise and cost-effective foundation designs. This paper represents an effort to apply the Hypoplasticity model to study the uplift capacity of single-helix helical piles. By comparing the numerical results with experimental data, the accuracy of this model is assessed.

2 CONSTITUTIVE MODEL

The Hypoplasticity model represents an advanced constitutive framework for capturing the complex behaviour of sand. The model was first proposed by von Wolffersdorff (1996) and later improved by Niemunis and Herle (1997) with introducing the intergranular strain state variable. It can capture the stress and void ratio states of sand during installation and subsequent loading stages and it has been successfully verified and applied in various geotechnical problems (e.g. Pucker et al., 2013; Staubach et al., 2021; Staubach et al., 2022). This model has 13 parameters: critical friction angle of sand (φ_{cr}), granular hardness (h_s), exponent of limiting void ratio curves (n), reference minimum void ratio (e_{d0}), reference critical void ratio (e_{c0}), and reference maximum void ratio (e_{i0}), dependency of peak friction angle on relative density (α), and dependency of stiffness on relative density (β). Additionally, it includes five parameters that represent the intergranular strain concept (m_R, m_T, R, β_r, χ).

3 IMPLEMENTATION OF THE MODEL IN THE NUMERICAL SIMULATION OF UPLIFT RESPONSE

To assess the reliability of the constitutive model in predicting the uplift capacity of helical piles, a number of centrifuge tests conducted by Hao et al. (2019) were numerically simulated, and the numerical predictions were compared with experimental data. Hao et al. (2019) aimed to minimise potential installation effects by pre-embedding the helical piles in the testing chamber during sand preparation (a method known as “wished-in-place” pile installation) and conducted the centrifuge tests at 20g. The prototype diameters of the helices, D_h, and the shaft, D_s, were 400 mm and 94 mm, respectively. The prototype pitch of the helix, p, was 100 mm.

3.1 Model parameters

Hao et al. (2019) used superfine silica (SFS) sand (median particle size D_{50} = 0.25) in their tests. The sand was dry and prepared in a very dense state (85% < D_r < 89%, where D_r is the relative density). The parameters of Hypoplasticity model for this sand were calibrated and presented by Pucker et al. (2013). The resulting parameters are summarised in Table 1.

Table 1. Constants of the hypoplastic model for SFS sand.

Parameter (unit)	Value
φ_{cr} (degree)	30
h_s (MPa)	1354
n	0.34
e_{d0}	0.49
e_{c0}	0.76
e_{i0}	0.86
α	0.18
β	1.27
m_R	5.16
m_T	3.07
R	1×10^{-4}
β_r	0.58
χ	5.74

Figure 2 shows the results of triaxial tests on dense samples of SFS sand (documented in Chow et al. (2019)) with corresponding simulations using the Hypoplasticity model. The results are presented in terms of the variation of deviatoric stress (q) with axial strain (ε_1) as well as variation of volumetric strain (ε_v) with axial strain at different confining pressures (p). The results indicate that the adopted hypoplastic model demonstrates a good agreement with the experimental data. More specifically, the model captures the peak stress of the samples well and effectively reproduces the post-peak softening behaviour. This capability is critical for accurately simulating the deformation mechanism and predicting the response under loading conditions. The hypoplastic model shows some discrepancies in replicating the volumetric strain behavior of the dense samples. This is mainly due to the fact that the parameter α, which governs these curves, was calibrated specifically to match the peak stress of the tests.

3.2 Finite element modelling

ABAQUS finite element software was used to develop numerical simulations in this study. According to previous works (Al-Baghdadi, 2018; Hao et al., 2019), the loading behaviour of anchors with circular and helical plates exhibits similar characteristics. Therefore, the helix was simplified to circular plate, and consequently, the problem can be simulated in 2D axisymmetric space. Four centrifuge tests on single-plate helical piles with varying embedment depth ratios (H/D_h) of 3, 6, 9, and 12 were simulated, where H is the depth from the soil surface to the midpoint of the helical plate.

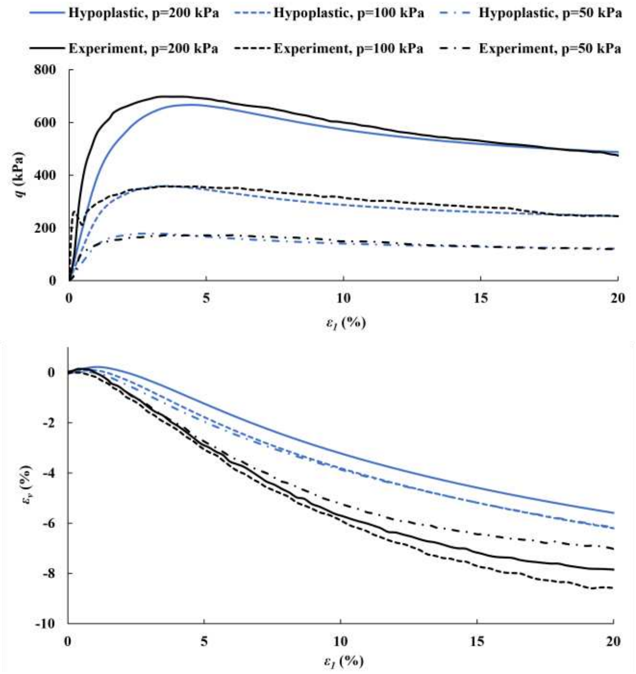

Figure 2. Comparison of triaxial test results measured from experiments with predictions from the hypoplastic model.

The helical pile was modelled as a rigid body and meshed with 2-node linear axisymmetric rigid (RAX2) elements. The soil medium was discretised with 4-node, axisymmetric, bilinear, quadrilateral, reduced integration (CAX4R) elements, with domain dimensions large enough to avoid boundary effects. A finer mesh zone with an element size of $0.02D_h$ was used near the pile, where intense plastic deformations occur during extraction. The bottom boundary of the soil was fixed in both horizontal and vertical directions, while the lateral boundary was constrained solely in the horizontal direction. A general contact model was used for the simulation of soil-pile interface contact. In this model, a hard normal contact condition controls the normal direction contact, while Coulomb friction law with skin friction angle of 0.65 of the peak friction angle governs the tangential contact behaviour. This estimation is the mean value of skin friction coefficients between dry dense sand and steel material with smooth and rough surface conditions (Potyondy, 1961).

The simulations were conducted in two steps. In the first step, the geostatic equilibrium was established by considering a lateral earth pressure coefficient of $k_0 = 1 - \sin\varphi_{cr} = 0.5$. Then, a tension load was applied to the helical pile using a fixed velocity rate of 0.5 m/s until failure was reached. Adopting this penetration rate caused a decrease in the computational cost while preserving solution accuracy (Fan et al., 2018). Figure 3 shows the finite element model for a typical case of $H/D_h = 6$, consisting of 42010 CAX4R and 125 RAX2 elements.

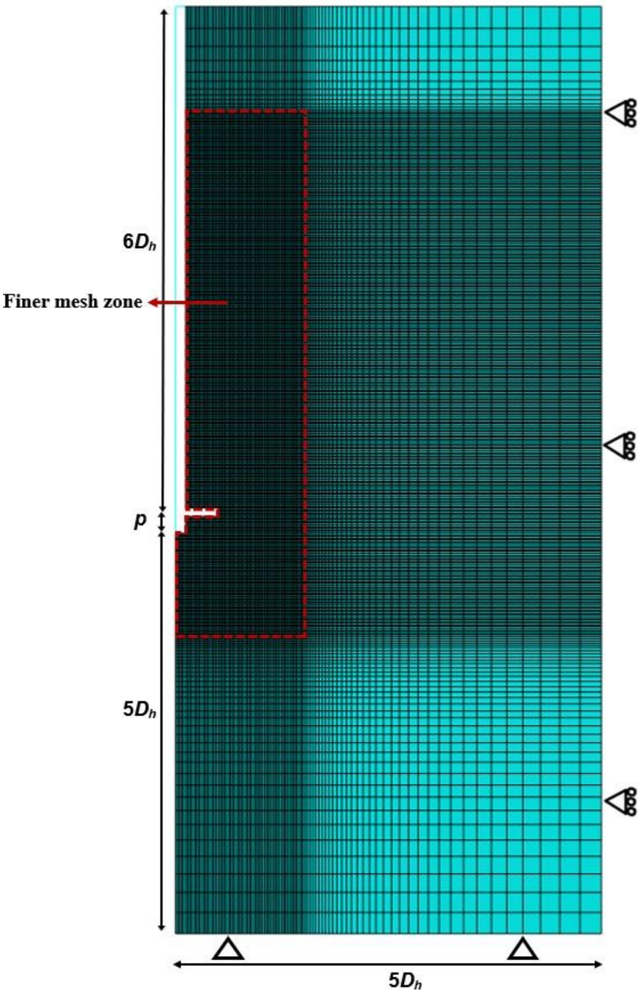

Figure 3. Finite element model.

4 RESULTS AND DISCUSSION

4.1 Uplift capacity

Figure 4 illustrates the load-displacement curves obtained from centrifuge tests and the predictions made by the numerical model in this investigation. In this graph, Q represents the uplift force, and u is the pile displacement during extraction. The results indicate that as the embedment ratio increases, both the experimental and predicted load-carrying capacities increase significantly. For $H/D_h = 3$ and $H/D_h = 12$, the numerical model performs reasonably well in simulating the uplift loading response of helical piles. Also, for $H/D_h = 9$, despite some discrepancies, the model could predict the general trend (with the average difference of less than 15%).

But, for $H/D_h = 6$, though the initial stiffness is quite consistent, the model overpredicts the loading response at larger displacements.

The uplift capacities (Q_t) for different depths, obtained from both centrifuge tests and numerical simulations, are presented in Table 2. The uplift capacity was defined using the criteria of 10%-Diameter (ISSMFE Subcommittee on Field Laboratory Testing, 1985; British Standards Institution, 1986; International Code Council, 2020), which specified that the ultimate uplift bearing capacity is determined as the load inducing an upward displacement of $0.1D_h$. The highest difference between the measured and predicted uplift values was 16%, indicating that the Hypoplasticity model has good potential in accurately predicting the uplift capacity of helical piles.

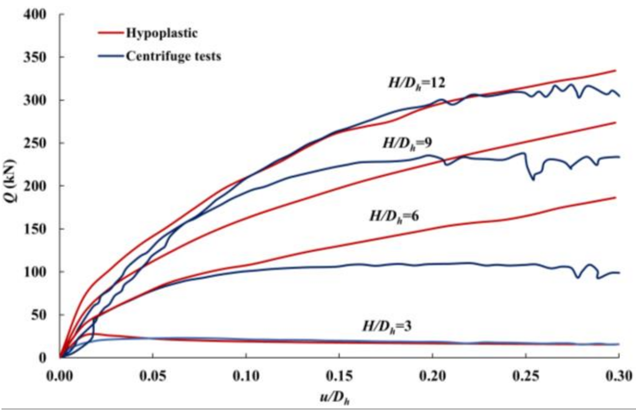

Figure 4. Comparison of the load-displacement curves measured from centrifuge tests with predictions from the hypoplastic model.

Table 2. Measured and predicted uplift capacities of helical piles

H/D_h	Q_t (kN)		
	Centrifuge test	Hypoplastic	Difference (%)
3	21	19	10
6	101	108	7
9	195	164	16
12	209	209	0

4.2 Failure mechanism

Figure 5 displays the contours of resultant displacement at failure ($u/D_h = 0.1$). As can be seen, for the shallow embedment depth, i.e., $H/D_h = 3$, the model exhibits a conical failure pattern extending to the soil surface, indicative of a shallow failure mode. For intermediate-depth ($H/D_h = 6$) and deep embedment ($H/D_h = 9$ and $H/D_h = 12$) helical piles, the numerical model suggests a dominant deep failure mechanism. The failure zone for deep embedment piles exhibits a bulb shape with its size varies with the embedment depth.

To gain a more comprehensive understanding of the movement of sand particles, the vectors representing the displacement of sand particles at the failure state are depicted in Figure 6. As the distance from the helix increases both vertically and horizontally, the magnitude of displacement decreases, indicating a reduced influence of the helix on the surrounding soil. Furthermore, it is observed that soil particles on the underside of the helix exhibit a counterflow to the pullout force, converging towards the centre axis of the pile. The results also indicate that although displacement vectors near the shaft are vertical, with an increase in the distance from the shaft, there is a transition on the displacement vectors from vertical to nearly horizontal.

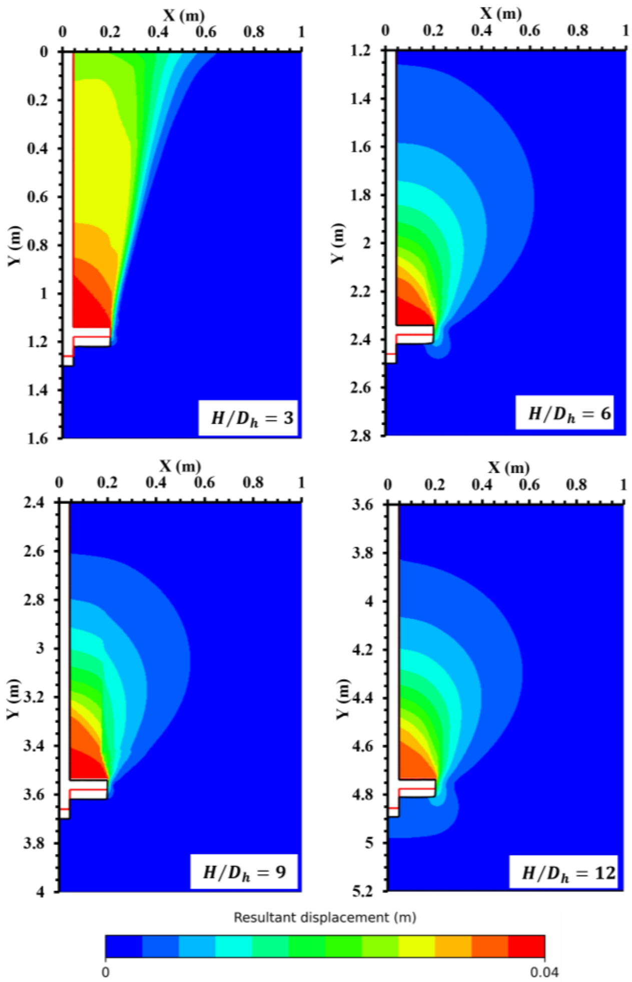

Figure 5. Displacement contours at the failure state.

4.3 Void ratio

The distribution diagrams of the void ratio of sand at the failure point, as captured by the Hypoplasticity model, are presented in Figure 7. For shallow embedment (i.e., $H/D_h = 3$), the void ratio increases along the failure surface, indicating significant soil loosening in this region. In cases of deeper embedment ($H/D_h \geq 6$), a triangular zone with initial void ratio is formed between the shaft and the upper edge of the helix. Beyond this region, with increasing radial distance from the helix, there is initially a zone of sand loosening, followed by a subsequent decrease in void ratio until transitioning to the initial value. Additionally, it is noted that the sand exhibits the highest values of void ratio (indicating the loosest state) in the vicinity of side edge of the helix.

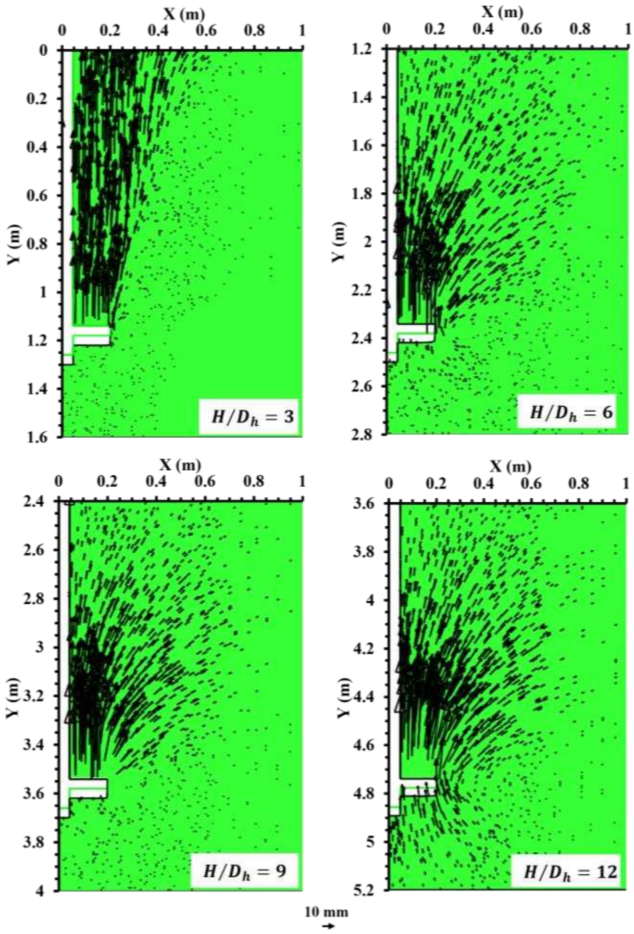

Figure 6. Resultant displacement vectors at the failure state.

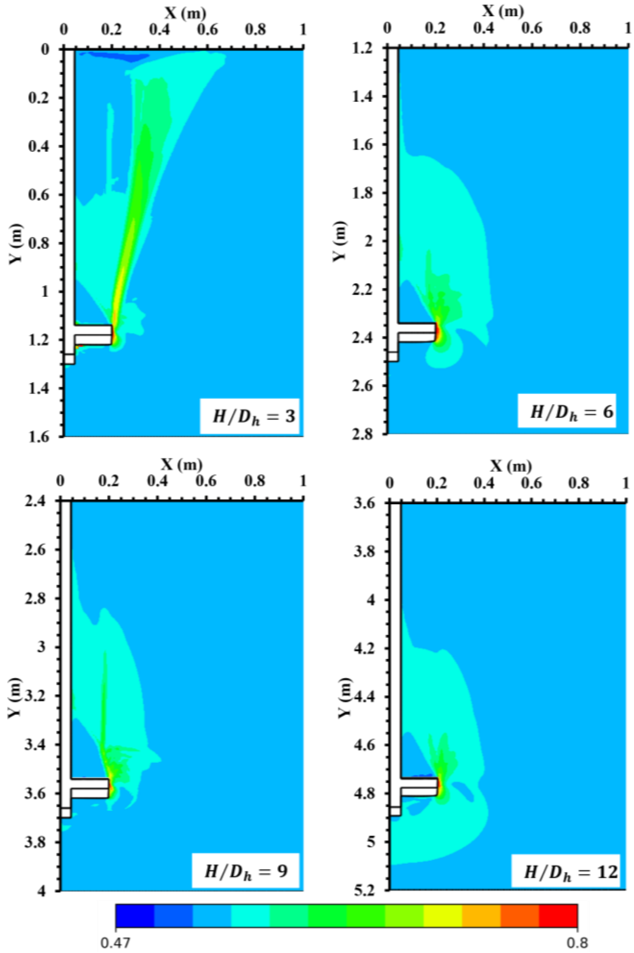

Figure 7. Contours of void ratio at the failure state.

5 CONCLUSIONS

This study presents simulations of centrifuge tests on single-helix helical piles subjected to uplift loading using the Hypoplasticity model. The model has been validated against triaxial test results, demonstrating its effectiveness in capturing post-peak behaviour, including softening and residual strength. Comparisons with centrifuge test results indicate that the model is competent in simulating the loading behaviour of helical piles. Additionally, it accurately models the dilation and contraction behaviour of sandy soils, which is crucial for predicting volume changes under various loading conditions. Consequently, the model provides reasonable predictions of uplift capacity and reliably captures failure mechanisms across different embedment depths. However, the validation was conducted using a single centrifuge test dataset, so further verification with field tests and different soil conditions would enhance the reliability of the approach. The effects of the installation procedure, including significant variations in the stress state and density of the soil, were not considered in this paper. Also, applying the Hypolasticity model to mulit-layered offshore soils remains challenging due to high computational costs and the need for extensive borehole and laboratory investigations.

Despite these constraints, this research advances the understanding of helical pile behaviour by employing an advanced modelling technique to analyse failure mechanisms and void ratio changes under tensile loading. The findings contribute to refining predictive models and developing improved design formulas in future studies. Ultimately, this research contributes to more accurate estimation of uplift capacity, reinforcing the feasibility of helical piles as a viable alternative for offshore foundations.

AUTHOR CONTRIBUTION STATEMENT

Mohsen Misaghian: Investigation, Software, Visualization, Writing- Original draft. **Pan Hu**: Conceptualisation, Methodology, Supervision, Writing- Reviewing and Editing. **Chin Leo**: Supervision, Writing- Reviewing and Editing. **Samanthika Liyanapathirana**: Supervision, Writing- Reviewing and Editing.

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