5th ECPMG
Delft · 2024

Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands

Challenges in numerical modelling of screw piles installation and vertical loading based on centrifuge testing

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ABSTRACT: Recent advancements in physical modelling have enabled a realistic representation of construction stages and installation procedures for complex geostructures. For instance, the process of precast pile installation, such as screw piles with potential in offshore engineering, has been persuasively replicated in centrifuge testing, allowing for the measurement of associated forces and displacements. On the other hand, numerical modelling has become a widely accepted approach for assessing soil-structure interactions, serving design purposes, or generating digital twins while numerical simulation of physical testing entails considerable challenges. Considering the geometrical details and the complex load transfer mechanism associated with screw pile installation, this paper discusses the challenges involved in the modelling of the pile installation process from the in-flight CPT test to the simulation of subsequent vertical loading, taking scaling aspects into account. As a result of this research, the paper will present appropriate strategies for simulating screw pile foundations with complex 3D geometries based on observations from physical tests.

1 INTRODUCTION

The stability and integrity of critical infrastructure relies substantially on the adequate performance of geotechnical assets, such as foundations and buried structures. With rapid changes in economic, social, and environmental aspects, greater emphasis is set on developing resilient and sustainable infrastructure. Damages to geostructures induced by seismic and dynamic events such as strategies to ensure sufficient resistance of shallow and deep foundations while keeping their resilience at the center of attention. Pile foundations of varying shapes and materials are often used, especially in cases of soft ground conditions, where the construction industry seeks foundations that feature efficient construction techniques and novel applications of materials. Among different types of piles with various methods of construction, helical piles have shown great potential for urban, onshore as well as offshore applications. The flexibility of the installation, negligible noise and vibration, during installation and installation-induced soil improvements in the vicinity of helical piles have made this deep foundation technology superior compared with other piling methods (Sakr and Bartlett, 2010, Perko, 2009).

Large-diameter helical piles (HP) offer efficient use of materials with optimum bearing capacity and are increasingly employed for supporting heavy and complex loading schemes (Figure 1). HPs can be attractive foundation options due to their high construction efficiency, low cost, and minimal installation-induced negative impacts (Perko, 2009).

The earthquake that happened in 2011 in New Zealand demonstrated the excellent performance of HPs in earthquake-prone areas; however, the main reason for such a remarkable performance is still uncovered (Cerato et al. 2017). To the best knowledge of the authors, the behavior of single and group helical piles in complex geotechnical conditions has not been sufficiently addressed. In recent years, HPs have been considered an appropriate type of deep foundation for offshore wind turbines (OWTs) (Byrne and Houlsby, 2015). Considering the complex interactions between the soil and helical piles during installation, physical testing and numerical modelling are essential to obtain better insight into the installation aspects and their impacts on the bearing capacity of helical piles with different forms and structures. In this context, Davidson et al. (2018) and Al-Baghdadi (2018) conducted a comprehensive study using the centrifuge device available at Dundee University on various forms of helical piles to evaluate the application of screw piles as an alternative foundation for offshore jacket structures.

Figure 1. a) Screw Piles used for Re-levelling and Strengthening existing Foundations after Quake Damage b) Screw Piles used for Anchoring (IPENZ, 2015)

However, the studies can be extended to evaluate the long-term behaviour of helical piles as foundations for OWTs or other onshore constructions under cyclic, dynamic, and seismic loadings. Additional studies are needed to show how the form of the helix can affect the bearing capacity of the pile and the rate of soil disturbance during pile installation (correct and incorrect helices, as defined by IPENZ, 2015). To address these uncertainties, combining physical modeling in state-of-the-art centrifuge facilities, full-scale testing, and advanced numerical modelling is vital. Nevertheless, numerical modeling of physical tests on helical piles, considering the complex geometry and sophisticated interactions with the deep foundation during upscaling, remains a challenging task.

The primary aim of this paper is to develop and calibrate an advanced 3D numerical model using validated results from physical modeling tests. This calibrated model is then employed to address additional uncertainties related to the behavior of helical piles. The model's accuracy is confirmed through comparisons with experimental data from centrifuge tests on single piles conducted at Dundee University. The paper presents the calibration process, highlights key challenges in numerical modeling, and provides preliminary results on the effects of helices and their arrangments on the lateral and vertical compression load-deformation behavior of piles.

2 METHODOLOGY

In this paper, the numerical modeling was carried out using the commercially available PLAXIS 3D package. To model soil behavior, the Hardening Soil model with small strain stiffness (HSsmall), proposed by Benz (2007), was employed. The application of the HSsmall model allows for accounting for the stress dependency of soil stiffness in primary, oedometric, as well as unloading and reloading states. The small strain feature of the model enables addressing the degradation of the soil shear modulus upon shearing, a critical aspect when the pile installation process is concerned.

3 DETAILS OF CENTRIFUGE TESTS

3.1 Materials

The sand used in the centrifuge modelling tests was Congleton HST95, fine silica sand that has γ_{max}= 17.58 kN/m^3, γ_{min}= 14.59 kN/m^3, D_{10} = 0.1 mm and D_{60} = 0.14 mm. Further details about this sand can be found in the works of Dundee University (e.g. Al-Baghdadi 2018).

3.2 Test setup

For the development of the numerical model, a series of centrifuge tests conducted at Dundee University to evaluate the effect of relative density and helices on the compression bearing capacity of piles. The tests were conducted on dry sand (HST95). The physical characteristics of this sand is described in Section 3. The air pluviation method was used to install the dry sand in the centrifuge box. Figure 2 shows the general shape of the helical piles used in the experiments.

The dimensions of the adopted screw pile with $S/D_h=1.25$ (where S is the distance between helices and D_h is the diameter of the helix) are shown in Figure 2, as an example.

The centrifuge tests were conducted under 50g acceleration, with the piles installed in the sand by applying vertical force and torque to the top of the pile until it reached the target depth of 200 mm. Afterwards, the bearing capacity of the piles was determined through additional loading. Further details on the centrifuge test procedure can be found in Al-Baghdadi (2018).

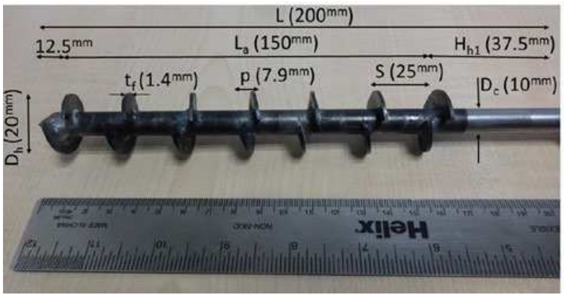

Figure 2. Dimensions of the adopted screw pile, as an example, MHP(S/Dh=1.25) (Al-Baghdadi 2018)

Figure 3 shows the compression load-settlement curves for piles with six different configurations: straight simple piles (SSP) with two different installation: (a) applying only compression force (push-in), and (b) applying force and torque (Rotation) for installation, see Al-Baghdadi (2018) for further details.

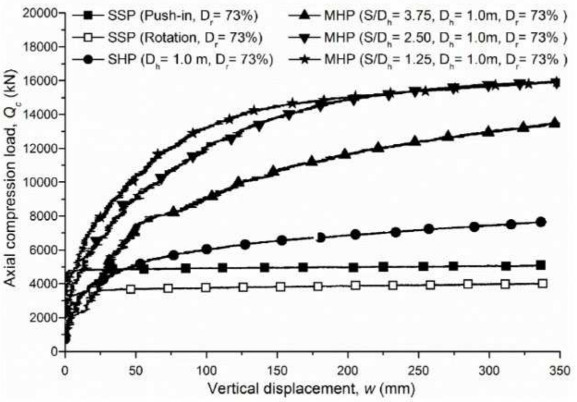

Figure 3. Vertical compression resistance of screw piles with different helical plates (Dr=73%) (Al-Baghdadi 2018)

The single helix pile (SHP), with the helix positioned close to the tips of the pile, and multi helix piles (MHP) among the types of piles considered in this experimental campaign. Their experiments were conducted on sands with three different relative densities, while this paper investigate the soil with relative density of 73%. Additionally, although piles with various diameters were tested, this research focuses on piles with a shaft diameter of $D_c=0.5$ m and a helix diameter of $D_h=1.0$ m after upscaling (Table 2).

4 CALIBRATION OF CONSTITUTIVE PARAMETERS

The parameters HSsmall model were adopted as described in Al-Dafae et al. (2013) and Al-Baghdadi (2018), where equations were developed with respect to the relative density to estimate the parameters of HSs model. The list of these Equations has been presented in Table 1.

Table 1. Parameters of HSsmall model (Al-Dafae, 2013)

Parameters	**HSs Parameters**
Drainage Type	Drained
$E_{oed}{}^{ref}$, MPa	$25D_r+20.22$
Second Stiffness, $E_{50}{}^{ref}$, MPa	$1.25\ E_{oed}{}^{ref}$
Unload/reload Stiffness, $E_{ur}{}^{ref}$, MPa	$3E_{oed}{}^{ref}$
Friction angle, [°]	$20D_r+29$
Dilation angle, [°]	$25D_r-4$
Poisson's ratio	0.2
Maximum Shear modulus, MPa	$50D_r+88.8$
Reference shear strain at $G/G_0=0.7$	$1{,}7D_r+0.67\ (\times 10^{-4})$
m	$0.6-0.1D_r$
Density, kN/m^3	$3D_r+14.5$

In this context, the numerical modelling on sand with relative density of $D_r=70\%$ have been conducted based on the equations listed in Table 1 by setting D_r equal to 0.7.

5 NUMERICAL MODELING OF CENTRIFUGE TEST AND ITS CHALLENGES

5.1 Idealization of model

To simulate the single pile problem, a 3D model with dimensions of 20 × 20 × 30 m was adopted as the domain for the pile model. The pile size in the centrifuge tests (Figure 2) was upscaled according to the centrifuge acceleration of 50g. Table 2 presents the dimensions of the shaft and helical plates of the piles, corresponding to those in the centrifuge setup shown in Figure 2.

The same as centrifuge tests on piles with $D_h=1.0$ and $D_c=0.5$ m (Figure 2), five pile configurations, namely SSP, SHP, as well as MHP with helix pitch (S) to helix diameter (D_h) ratio of S/D_h =3.75, 2.5, 1.25 are modelled. Figures 4 and 5 show the modelled piles in the current simulations. As seen in Figure 5, each pile has 16 parts to simply evaluate the effect of pile installation and with similar shape as in centrifuge tests (Figure 2). Figure 5 shows the dimension of the pile head while the rest 15 parts have also the same configuration and dimensions.

Table 2. Dimension of the piles in centrifuge, 50g and prepared model (Al-Baghdadi 2018)

Dimensions	Centrifuge (mm)	Model (mm)
Length	200	10,000
Shaft diameter	10	500
Helix space	25	1250
Helix diameter	20	1,000
Pitch	7.9	400
Plate thickness	1.4	70

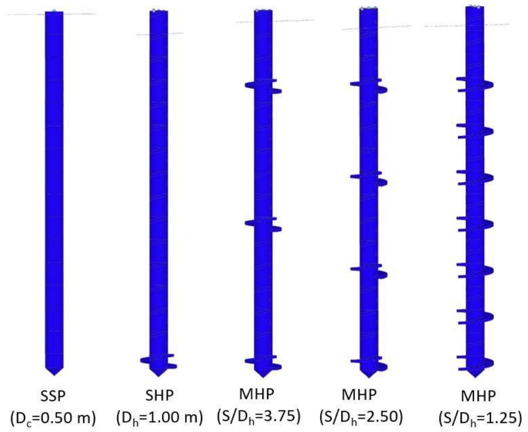

Figure 4. Piles in present numerical simulations

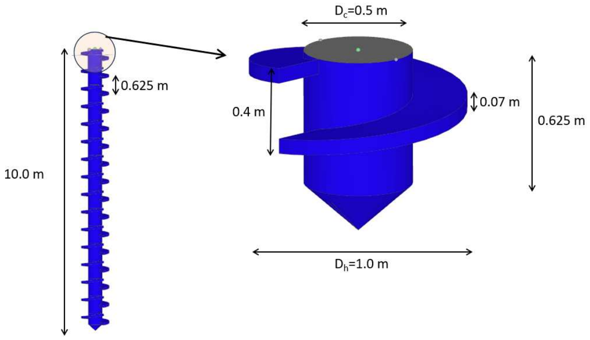

Figure 5. Modelled pile after upscaling the dimensions of physical test in centrifuge (Figure 2 and Table 2)

5.2 Neglecting the installation effects

After generation of the model geometry and assigning the material characteristics, the model was discretised to the total number of 100,000 to 150,000 elements depending on the number of helical plates.

Firstly, the pile behaviour under compressive loading was simulated without considering the pile installation procedure. In this context, a displacement of 0.3 m was applied to the piles, and the force-displacement curves were obtained from numerical models for all cases. As shown in Figure 6, the results from the numerical simulations are not comparable to the centrifuge measurements.

The predicted compression bearing capacity is significantly lower than the results obtained from the centrifuge tests. Further analyses were also conducted to evaluate the possible effect of helix form and pitch of the helical plates with the results presented in Figure 6. As seen, the numerical results indicate that the pitch of the helix does not significantly affect the bearing capacity of the helical piles, and all configurations produce similar results that are not comparable to the centrifuge measurements.

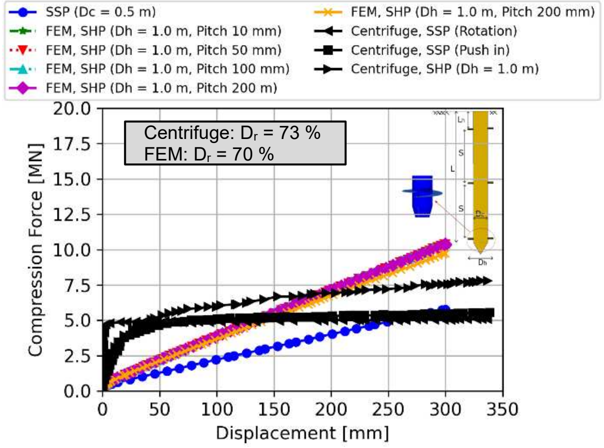

Figure 6. Numerical measurements using Hardening Small strain without considering installation effects in compared to the centrifuge measurements

5.3 Considering the installation effects

In the next step, the pile installation procedure was also incorporated into the numerical models. The installation forces applied in the centrifuge tests, including both vertical force and applied Torque during the pile installation in the physical model, were also incorporated into the numerical simulation. The installation load-penetration depth history reported from the experiments was digitized from Al-Baghdadi (2018) and is represented in the Figure 7. In this paper, for normal pile (SSP), only vertical force has been considered as installation force and for other piles vertical force and Torque have been considered as installation forces.

To address the installation process in numerical simulations, the piles were divided into 16 segments with the length of 0.625 m, as explained in section 5.1. To accurately mimic the gradual installation process, the procedure was divided into several calculation phases. In each phase, segments of the pile were consecutively activated along the pile depth, and the corresponding installation forces were applied to the head of the activated segments.

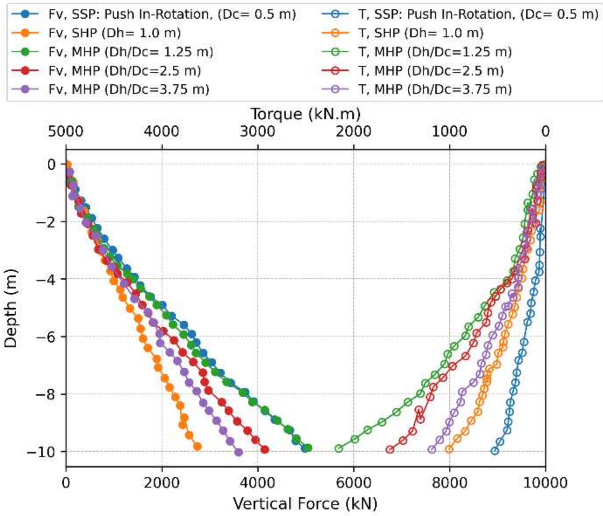

Figure 7. Adopted installation force and torque in centrifuge (modified after Al-Baghdadi 2018)

For instance, the first step of installation was modelled by activating the segment in the depth of 0 to 0.625 m and the vertical force and Torque corresponds to the depth of 0.625 m were applied and the calculation was pursued in this phase. In the next step, the second segment of the pile (till depth of 1.25 m) was activated, and the installation forces (according to Figure 7) was applied to the pile head. This method was consecutively continued to have all 16 segments of the pile activated and installed in the soil accomplish the pile installation. Figure 8 shows the total displacement of the pile after the activation of the second pile segment and applying the installation forces. The red arrows show the pile downward movement followed with rotation of the pile. In the step 17 (end of installation) all pile parts have been installed and activated, the installation forces were eliminated, and the installation-induced displacement were reset to zero. This process allowed the transfer of the installation stresses into the subsoil and mimic the stress evolutions in the ground as a consequence of the pile installation process. Afterwards, the bearing capacity of the pile was calculated by applying 0.1 m displacement to the installed pile head, where the ultimate bearing capacity is evaluated at 10% of pile diameter, which will be about 0.05 m for the adopted piles (assumed = 0.1D$_c$).

6 RESULST AND DISCUSSION

Figure 9 shows the distribution of the displacement in the ground upon compressive loading of SSP and MHP (D$_h$=3.75). As seen, the helixes significantly enhance the interactions between the pile and soil allowing for better load transfer from the pile to the ground.

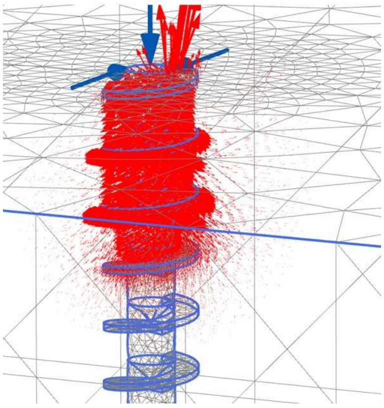

Figure 8. pile-soil displacement due to the simulation of installation procedure, (depth of 1.25 m from ground surface)

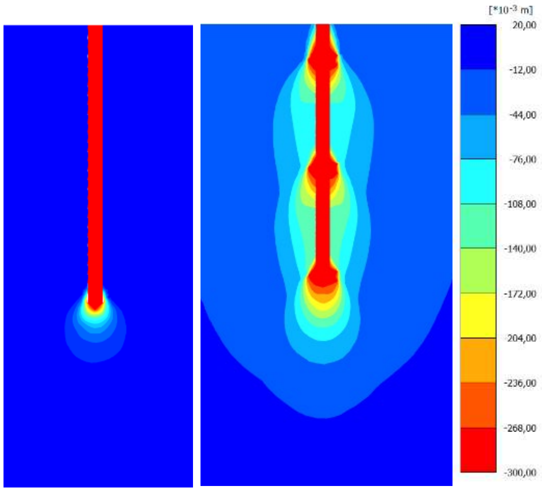

Figure 9. Displacement contours of a) SSP and b) Pile with 3 Helixes (MHP, S/Dh=3.75)

Figure 10 shows the comparison between the numerical and centrifuge results for different pile configurations under compression. As shown, the agreement between the computation and experiments can be significantly improved by accounting the installation process using the concept discussed in the previous section. As seen, the MHP piles have significantly higher bearing resistance against compression while the bearing capacity increases with an increase in the settlement in a larger range of displacement.

In other words, as larger displacements are applied, more helices become mobilized, leading to an increase in the bearing resistance of the deep foundation.

After validation of the model against centrifuge results for compressive loading case, the piles with different configrations have been subjected to a horizontal loading. The numerical results for piles under horizontal loading are shown in Figure 11. As shown, the helical piles indicate higher later bearing resistance. However, though the number of the helixes slightly improves the performance of the pile under lateral loading, the configuration of the helixes does not significantly enhance the lateral behaviour.

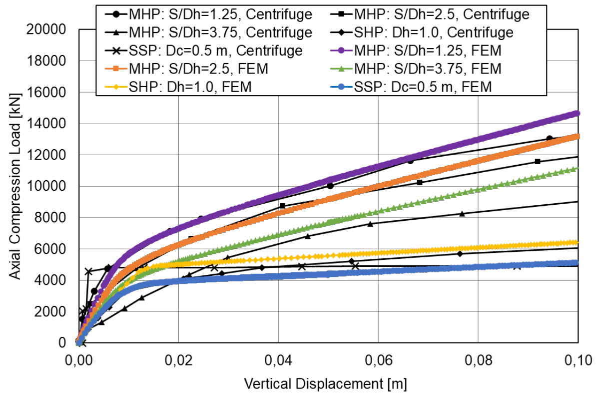

Figure 10. Load-settlement behaviour of the SSP, SHP and MHP piles from numerical simulations and Centrifuge data considering the effect of installation

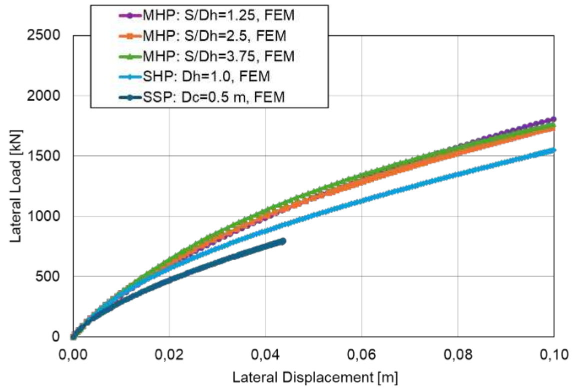

Figure 11. Lateral load-settlement behaviour of the SSP, SHP and MHP piles from numerical simulations and Centrifuge data considering the effect of installation

7 CONCLUSIONS

The paper discussed the calibration process and highlighted the main challenges encountered in numerical modeling.

The results demonstrated the significant impact of the pile installation process on the bearing capacity of piles, which can be captured by applying installation forces incrementally in the model.

The results revealed a significant increase in the bearing capacity of helical piles under axial compression, which further increased with the addition of more helical plates. However, the differences between numerical and centrifuge measurements tended to grow at large deformations. This might be due to the mobilization of more helices at large deformations.

Finally, helical piles exhibited greater lateral bearing resistance compared to non-helical configurations. While an increased number of helices slightly improved lateral performance, the specific configuration of the helices did not significantly enhance lateral behavior.

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