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Study on the installation effect of helical piles in very dense sand

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ABSTRACT: The increasing interest on the use of helical piles to support offshore facilities has motivated the development of researches on this type of foundation. Literature presents some studies on helical piles in dense sand that disregard the effects that pile installation could cause on soil as a “wished-in-place” condition is considered. Normally this condition is adopted because of the difficulty in reproducing the pile installation according to the in-situ procedure. However, some previous studies have shown that the failure mechanism in uplift is controlled by the disturbed-non disturbed condition of the soil around the pile, mainly for dense sand condition. On the other hand, the literature also brings some studies arguing that the pile installation little influences both failure mechanism and uplift performance. Therefore, the current study uses results of centrifuge modelling to compare the monotonic uplift performance of single-helix piles in very dense sand installed via two different procedures: i) by placing the model pile during sand bed pluviation, which intends to avoid any soil disturbance (“wished-in-place” condition) and; ii) by screwing the model pile in flight with torque and downward crowd force applied simultaneously. The results show that the model pile installed in flight showed uplift capacity at least 60% greater than the “wished-in-place” model pile, also accompanied by a greater axial stiffness. The unexpected poorer performance of the “wished-in-place” model piles suggests that the model may have acted as an obstacle for the sand grains during pluviation, which resulted in density variation of the sand around the model and, consequently, provided lower uplift capacity compared to the in-flight installation case.

Keywords: Helical Piles; Sand; Soil Disturbance; Installation Procedure, Centrifuge Modelling.

1 INTRODUCTION

Because of the increasing interest on the use of helical piles in both onshore and offshore structures, many questions and issues have been raised. In this scenario, centrifuge modelling has been an important tool for the study of helical piles since it allows for parametric studies reproducing the same field of forces and mass in a full-scale structure with closely controlled test conditions (Garnier, 2001). However, reliable simulations of the pile behaviour depend on replicating the in-situ soil conditions (e.g. deposition process, stress history) and the pile installation procedure, in addition to avoiding scale effects.

Helical piles are installed by screwing it into the ground usually using a hydraulic motor attached to a backhoe loader or a rotary rig equipment. Consequently, the soil penetrated by the pile experiences displacement and shearing, which can cause changes in the soil around the pile. Based on a simulation via Discrete Element Modeling, Sharif *et al.* (2019) noted that pile installation modifies the sand density close to the pile, with the relative density (D_r) changing from 80% to 55%.

In centrifuge tests with single and multi-helix model piles in sand, Tsuha *et al.* (2012) observed that the contribution of the upper helices to the uplift

capacity is less important in dense sand than in loose sand. This finding suggests that, in addition to the interaction between helices (Hao *et al.* 2019), the difference in compactness is considerable if the dense sand is traversed by a helix one, two or three times. However, for loose sand, the penetration of the lower helix shall loosen totally the sand inside the cylinder circumscribed the helix. As a result, the sand above all the helices present equivalent sand disturbance and, consequently, similar compactness. The above observations highlight the importance of reproducing the prototype installation to replicate the disturbance caused on dense sands.

Gavin *et al.* (2014) reported full-scale load tests on single-helix piles in dense sand and analysed the results using Finite Element (FE) Modelling. Under compressive loading, the numerical simulation showed very good agreement with the experimental result in terms of load-displacement response. Under uplift loading, in contrast, the numerical simulation overpredicted both axial stiffness and uplift resistance. According to the cited authors, the parameters of sand used in the FE model derived from triaxial compression tests and, therefore, provided a very good prediction in compressive loading. In this case, the soil below the helix, which controls the pile response, is relatively unaffected



Figure 1. Helical pile models

by the installation. For the uplift case, however, the sand above the helix experience disturbance during installation. Consequently, the parameters from the triaxial tests with undisturbed samples are not suitable to be assigned for the disturbed sand above the helix.

The hypothesis by Gavin *et al.* (2014) was investigated in the study of Pérez *et al.* (2017) that showed that assigning modified values for the parameters of disturbed soil can provide good agreement with experimental results. In contrast, when the installation effect is neglected and undisturbed sand parameters are considered, the uplift capacity is overpredicted.

The testing campaign reported here was designed to evaluate the installation effect on the sand condition and, consequently, on the uplift load-displacement response of the single-helix model piles. To isolate the installation effect, the model piles were installed via two different procedures and then tested in uplift loading. At first, the model piles under “wished-in-place” condition (no installation effect) were expected to exhibit larger ultimate load compared to the model piles installed simulating the *in-situ* procedure. However, the results have shown the opposite. Therefore, the current paper aims to discuss the experimental procedure and results to contribute to future experiments.

2 MATERIALS AND METHODS

The centrifuge testing conducted for the current study was undertaken using the IFSTTAR geocentrifuge. Different g-levels for three single-helix pile models of different sizes were used to simulate the same prototype. In addition to the comparison of two different installation procedures, the use of different model sizes aimed to ensure the non-occurrence of scale effects.

2.1. Model piles

The current tests simulated a single-helix pile prototype with a helix diameter $D = 330$ mm, a shaft diameter $d = 100$ mm, and installed with a helix depth $H = 8D$. Helix and shaft diameters were established to provide a helix-to-shaft diameter ratio (D/d) equals to 3.3, which is a common value for

helical piles used for onshore structures.

The helical pile models consist of a single helical plate welded to the tip of a round rod, both steel fabricated (Fig. 1). Table 1 presents the dimensions of the three model piles. Both pitch (p) and thickness (t_h) of the helical plates are not scaled according to the dimensions of the same prototype. The model HP1 was used in previous research conducted in the same laboratory (Tsuha, 2007), and the other two models were fabricated later for the research of which the present study is part (Schiavon, 2016).

2.2. Sand bed

The sand used in the experiments is the HN38 fraction of Hostun sand, which is a very fine and uniform silica sand extracted from deposits located in the commune of Hostun, France. Table 2 presents some characteristics of the Hostun sand. The model piles were tested in dry sand beds reconstituted by means of the raining deposition technique, in which dry sand is placed in an automatic hopper and pours through a slot to produce a uniform sand rain over a container.

Table 1. Dimensions of helical pile models.

Model pile	D (mm)	d (mm)	p (mm)	t_h (mm)
HP1	20.0	6.0	1.6	0.5
HP2	26.6	8.0	1.4	0.8
HP3	33.0	10.0	1.5	1.8

Table 2. Characteristics of HN38 Hostun sand.

Parameter	Unit	Value
Specific gravity of particles, G_s	-	2.64
Maximum dry density, $\rho_{d(max)}$	kg/m ³	1554
Minimum dry density, $\rho_{d(min)}$	kg/m ³	1186
Average grain size, d_{50}	mm	0.12
Coefficient of uniformity, C_U	-	1.97
Angle of friction*, ϕ	deg.	47

*from triaxial tests with D_r between 90% and 95% and confining stresses of 50 kPa, 100 kPa and 200 kPa.

The hopper moves into roundtrips while the sand deposits on the container bottom. Hopper horizontal speed and slot width are the parameters set to

control the drop height and the flow rate of sand. The pluviation process is known for providing homogenous specimens and good repeatability (Garnier, 2001; K us, 1992; Miura and Toki, 1982).

The final dimensions of the sand bed are 1200 mm in length, 800 mm in width and 360 mm in depth. To assess the achieved density, at least two density pots were placed on the container bottom. The average relative density (D_r) of sand beds resulting from sand raining ranged from 95% to 99%.

2.3. Installation and testing of model piles

Two different procedures were followed to install the model piles at an embedment ratio $H/D = 8$ (where H is the helix embedment depth), which is expected to provide an intermediate behaviour between shallow and deep anchor (P erez *et al.* 2017). The first procedure consisted of pausing the pluviation, positioning the model piles on the sand bed surface, and then recommencing the pluviation (Fig. 2). The use of this procedure aimed to evaluate the performance of the model piles in a sand bed unaffected by the model pile installation, which is recognised here as the “wished-in-place” (WIP) condition. Two nylon threads were used passing laterally the top of each model pile to ensure verticality. Figure 2 shows the positioning of models during the pluviation. The whole procedure is carried out at $1\times g$ outside the centrifuge.

The second procedure is similar to that reported in current authors’ previous studies (e.g. Tsuchi and Aoki, 2010; Schiavon *et al.*, 2016). In this procedure, the model anchors are screwed into the sand bed similarly to field practice (SCR condition). The vertical feed rate corresponds to 1 helix pitch per revolution, with a rotating rate of 5.3 rpm (0.56 rad/s). The whole procedure is carried out under macro-gravity (in flight).

In both procedures, a minimum centre-to-centre spacing of $10D$ was kept between model piles.

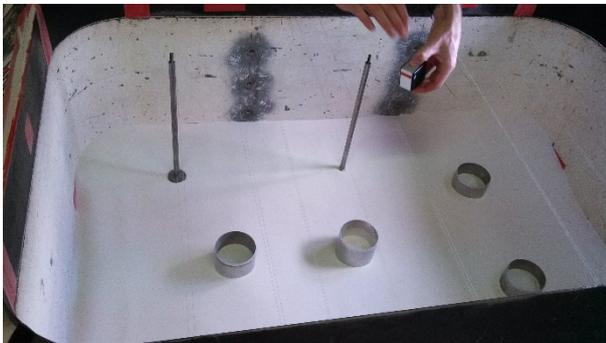


Figure 2. Sand bed preparation for WIP condition.

Before the first test in the container, three cycles of centrifugation taking three minutes each were conducted up to the maximum g-level the

container was expected to be subjected. The vertical displacement rate for pull-out tests was 0.3 mm/s at model scale.

3 RESULTS AND DISCUSSION

Figures 3 to 5 present the load-displacement response, at prototype scale, for the monotonic uplift tests with models under condition “wished-in-place” (WIP) and screwed into the sand bed in flight (SCR).

Since the use of WIP condition intended to avoid any soil disturbance caused by the model pile installation, both axial stiffness and ultimate load were expected to be larger than those obtained with the SCR condition. However, regardless the anomalous behaviour observed for the 8FH SCR test with uplift displacement between 5 and 20 mm (Fig. 4), the model piles exhibited lower stiffness for the WIP condition.

Moreover, the WIP condition resulted in significantly lower ultimate uplift load (Q_{ult}) compared to the SCR condition. The values of Q_{ult} for the WIP condition are respectively 63%, 65% and 40% lower than those of SCR condition.

Table 3 summarises the results of the monotonic uplift tests. The larger values of Q_{ult} for HP3 WIP and HP1 SCR are likely due to sand bed heterogeneity, and not necessarily scale effect since no trend with increasing size can be identified. Despite the dispersion, the results indicate a tendency of WIP condition to provide lower ultimate load and stiffness in monotonic uplift tests compared to the SCR condition.

The unexpected lower axial stiffness and ultimate load for the WIP tests may be due to possible local changes in density around the pile resulting from “umbrella” effects (Hao *et al.*, 2019). Similar effect on density is observed in the vicinity of the container walls, where the sand bed is less dense compared with the central zone of the container.

Ternet (1999) verified inhomogenous zones in the periphery of sand beds reconstituted via sand

Table 3. Results of uplift model tests (prototype scale).

Test	Cont. No.	$D_{r, avg}$ (%)	H/D	Q_{ult} (kN)	$U_{(peak)}$ (mm)
HP1 WIP	1	95	8	38.5	45.9
HP1 SCR	4	99	8	104.5	49.7
HP2 WIP	1	95	8	31.4	51.2
HP2 SCR	2	96	8	89.3	99.4
HP3 WIP	1	95	8	55.8	52.6
HP3 SCR	3	96	8	88.0	63.9

raining in containers similar to those of the current study. In addition to the action of air vortices on the falling grains, the sand deposition with reduced

kinetic energy in those zones results from the collision of grains with the container walls.

In the current work, however, no wind vortex is assumed to occur near the model piles because the tests were carried out in a zone free from boundary effects on the sand deposition. Therefore, the model piles may be acted as an obstacle for the falling grains that collide with the pile top and side.

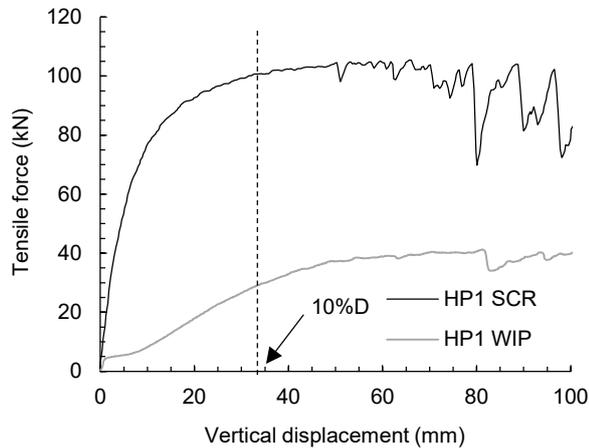


Figure 3. Load-displacement responses for HP1 model.

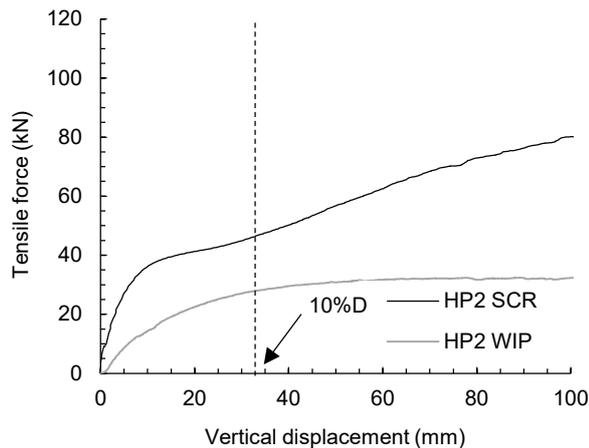


Figure 4. Load-displacement responses for HP2 model.

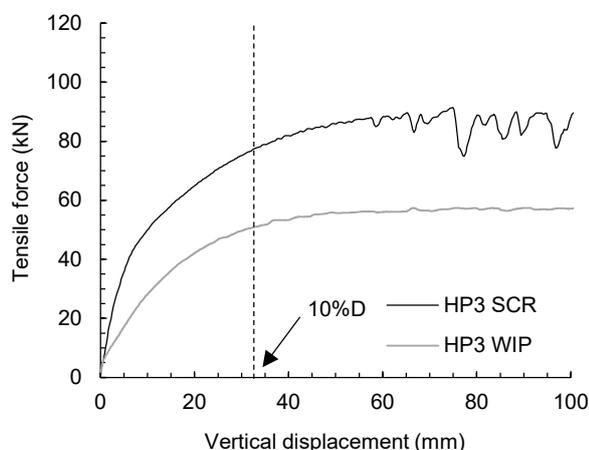


Figure 5. Load-displacement responses for HP3 model.

After collision, the sand grains lose kinetic energy and change direction. Consequently, the sand grains

are deposited in a less dense assembly than the rest of the sand bed. In addition, a small amount of sand grains can remain deposited in a loose state on top of the model pile, which can further reduce the kinetic energy of falling grains.

Figure 6 shows photos from a quick experiment conducted with fine silica sand and a threaded rod with 9.3 mm in diameter. Sand rain was simulated similarly to the procedure described in Miura and Toki (1982), but with no volume control of rain flow. The sand rain was recorded in slow motion video aiming to observe the movement of grains after colliding with the rod. The figure shows that significant change of direction occurs for the grains colliding with the rod. In addition to the loss of kinetic energy with the collision with the rod, deflected grains can strike other free falling grains (with no previous collision) and, thus, cause a chain of collision events, which will result in a broader effect of deposition with reduced energy.

For investigations considering the “wished-in-place” condition using sand pluviation for the sand bed preparation, “umbrella” effect could be minimised by dividing the pile shaft into extension segments and attaching them to the pile composition each time the sand bed height reaches the targeted location for the next segment. This procedure was conducted in the study of Hao *et al.* (2019) with single and multi-helix pile models in sand. The above-mentioned procedure can minimise but not eliminate variations on sand density, since short shaft segment extensions can also cause “umbrella” effects. Alternatively, when the sand deposition via pluviation is not a requirement for the WIP condition, the sand bed could be prepared with compaction, vibration or a combination of both.

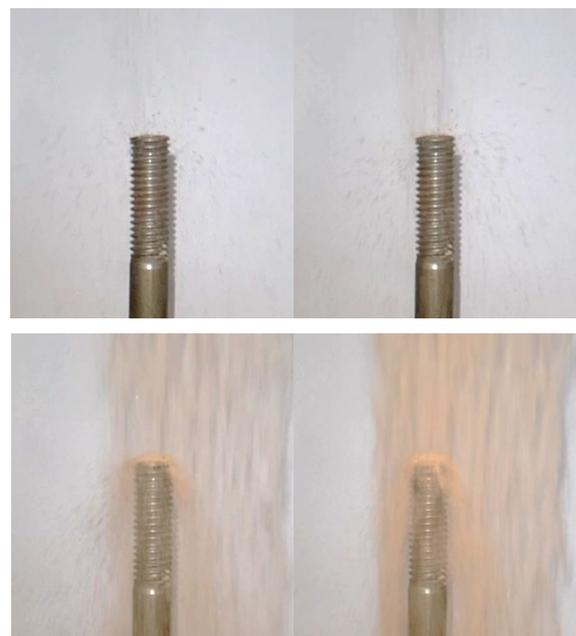


Figure 6. Pluviation of fine sand over a rod.

3.1. Comparison with numerical simulations

A Finite Element modelling in axisymmetric condition was conducted to simulate the helical pile as a “wished-in-place” element. Two different set of characteristics for the sand mass were considered in order to compare numerical and experimental results. The characteristics assigned for pile and sand are listed in Table 4.

Table 4. Sand parameters for numerical simulations.

Sand parameter	FE model 1	FE model 2
γ (kN/m ³)	15.3	15.3
E_{50}^{ref} (kPa)	5.0×10^4	2.2×10^4
E_{oed}^{ref} (kPa)	2.6×10^4	2.0×10^4
E_{ur}^{ref} (kPa)	1.0×10^5	6.0×10^4
m	0.5	0.5
ν_{ur}	0.2	0.2
p^{ref} (kPa)	100	100
K_0^{NC}	0.32	0.5
R_f	0.9	0.9
c_{ref} (kPa)	1.0	1.0
ϕ (deg.)	47	30
ψ (deg.)	17	1

where, E_{50}^{ref} = secant stiffness in standard drained triaxial test, E_{oed}^{ref} , tangent stiffness for primary oedometer loading, m = power for stress-level dependency of stiffness, E_{ur}^{ref} = unloading/reloading stiffness, ν_{ur} = Poisson's ratio for unloading-reloading, p^{ref} = reference stress for stiffnesses, K_0^{NC} = coefficient of earth pressure at rest for normal consolidation, R_f = failure ratio.

The constitutive model used for the sand was the Hardening Soil Model, HS-soil (Schanz *et al.*, 1999). The FE model 1 uses the parameters for the undisturbed HN38 Hostun sand, as listed in Table 1. The sand parameters for the FE model 2 were determined through a parametric study searching for a pile load-displacement response with reasonable agreement with those from the WIP tests. The simulation of these two conditions aimed to demonstrate the difference between the values of parameters if an undisturbed condition (FE model 1) were in fact achieved.

The pile element was modelled as linear-elastic material having Young's modulus $E = 2.0 \times 10^8$ kPa and Poisson's ratio $\nu = 0.3$. Interface elements were assigned to the pile-sand interface with interface angle of friction $\delta = 20$ deg. in both FE models.

Both sand and pile were modelled with 15-node solid elements. Meshing update technique was used to avoid excessive mesh distortion.

Figure 7 compares the experimental results in WIP condition with the numerical ones. The FE model 1 resulted an uplift resistance significantly larger than the 6 experimental tests. On the other

hand, good agreement with experimental results was obtained when the sand parameters corresponded to the constant-volume shearing condition (FE model 2), which may be compared to the loose state of sands.

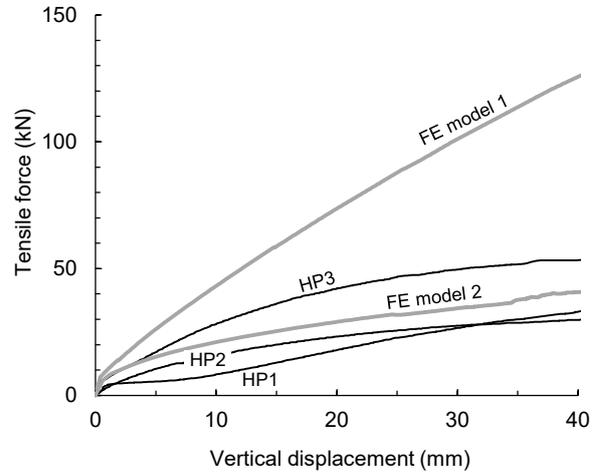


Figure 7. Load-displacement responses from numerical and experimental tests with WIP condition.

4 CONCLUSION

The current study intended to investigate the installation effects of helical pile models in very dense sand. Model piles were subjected to uplift loading in centrifuge after being installed during the sand bed preparation (“wished-in-place” condition – avoiding installation effects) or installed in flight by screwing it into the sand bed.

The pile models at “wished-in-place” condition exhibited lower ultimate uplift load, which at first could lead to the conclusion that the screwing process causes strength increase of the soil around the pile. This is not the case. The model piles positioned on the surface of the sand bed during pluviation (WIP condition) caused umbrella effects on the sand deposition around the models. As a result, local soil density variation occurred in the sand.

The findings emphasize the importance of the sample preparation to reproduce the intended test condition and, thus, avoid misinterpretation of results.

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