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Centrifuge modelling of installation effects on helical anchor performance in sand

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ABSTRACT: Helical anchors are installed in the field by means of torque application, and during the installation, the soil traversed by the helices experiences torsional and vertical shearing. Considering that the uplift capacity of helical anchors depends mainly on the shear strength of the disturbed soil mass above the helices, an evaluation of the effect of the soil modification on the anchor capacity, caused by the installation procedure, is helpful to the understanding of helical anchor performance. The present investigation was conducted to examine this effect of installation on the uplift capacity of helical anchors in sand by centrifuge model tests. The influence of helix diameter and of sand's initial density on the degree of loss in the helix uplift bearing capacity, due to sand disturbance, were evaluated. In addition, the results indicate that dimensionless pull-out capacity factor, typically used to estimate helical anchor capacity, varies with the helix diameter.

1 INTRODUCTION

1.1 *Helical anchors*

Helical anchors have been used to sustain tension loads for different types of structures. Uses for helical anchors include transmission towers and cell phone towers, utility guy anchors, braced excavations, retaining wall systems, and many other structures.

This type of anchor is composed of helical circular steel plates welded to a steel shaft (Fig. 1), and installed into the ground by application of torsion to the upper end of the shaft. If necessary, extensions sections are used to advance the lead section (with one or multiple helical bearing plates) deeper into the soil.

Figure 1. Helical anchor.

For multi-helix anchors, the helical plates are welded to the shaft at a predetermined spacing. The number and diameters of plates are estimated according to the soil characteristics to provide a required uplift capacity.

1.2 *Installation effects*

The uplift capacity of helical anchors increases with the number of helices when calculated by the available prediction methods. On the other hand, field tests have shown that in some cases the addition of one or more helices to the helical anchor does not augment its uplift capacity in the same manner predicted during the design phase.

This fact can be explained by the soil disturbance caused by the installation of helical anchors. These anchors are installed in the field by means of torque application, with a rate of penetration of approximately one pitch per revolution, in order to minimize shearing of the soil. However, the helical pile installation disturbs the soil structure and changes the stresses in the soil mass. During helical anchor installation; the soil penetrated by the plates is sheared and displaced.

Komatsu (2007) conducted laboratory model tests on a small scale helical anchor to examine the effect of anchor installation on the soil penetrated. From these tests, this author observed the following: (i) the soil above the blade of the anchor rises upwards, (ii) the soil close to the anchor shaft is pulled down due to the shaft friction, and (iii) the soil beneath the blade is compressed.

Previous experimental investigations on helical anchors (Clemence et al. 1994, Sakr 2009, and Lutennegger 2011) have indicated that the amount of increase in the uplift capacity of helical anchors with the increase in the number of helices is not as expected.

The gain in the uplift capacity of helical anchors due to the inclusion of one more helix is variable, and depends of the pile configuration, soil characteristics, and significantly of the degree of disturbance in the soil caused by anchor installation.

Also, the rate of capacity gain with the increase in the number of helices is nonlinear, since the disturbance caused by the anchor installation is usually more pronounced in the soil mass above the upper plates than above the lower plates, because the upper soil layers are penetrated more than once.

Mitsch & Clemence (1985) affirmed that the installation of helical anchors induces significant stress changes in sandy soil, and that these changes influence the anchor uplift behavior. Considering that changes in anchor capacity, experimental investigations are essential to the development of a complete understanding of this disturbance effect, and also to give accurate estimates of the helical pile capacity.

For this reason, the authors of this paper carried out centrifuge model tests to investigate the influence of helix diameter and sand's initial density on the contributions of the upper helical plates to the total anchor uplift capacity. These tests evaluate the relationship between the efficiencies of the upper helices and the effect of installation process on the uplift capacity of multi-helix anchors.

1.3 *Centrifuge tests to study helical anchors behaviour*

A limited number of centrifuge tests were carried out to evaluate the performance of helical anchors (Levesque 2002, Tsuha et al. 2007, Bian et al. 2008, Wang et al. 2010). Prior to helical anchors studies using centrifuge, few centrifugal model tests have been performed to study plate anchors behaviour (Ovesen 1981, Dickin & Leung 1983, Dickin 1988, Tagaya et al. 1988).

These centrifuge model studies on plate anchors provide important information about the behavior, mechanisms and design model aspects of helical anchors. However, as the plate anchors are installed by excavating the ground, placing the anchor, and then backfilling with soil, these tests cannot replicate the effect of helical anchor installation in the soil.

The changes due to the disturbance produced by screwing the helices into the soil influence considerably the uplift response of helical anchors. Therefore, centrifuge tests should be performed on helical anchor models, installed in the soil by torque application, as occurs in the field, to provide better representation of helical anchor behaviour.

Tsuha et al. (2007) carried out centrifuge model tests to verify the effect of installation process (screwing mechanism) on the multi-helix anchor uplift capacity. This manuscript presents a summary of the most important findings of this study on the installation effects based on centrifuge experiments.

2 TESTING ARRANGEMENTS AND PROGRAMME

The centrifuge model experiments were conducted on reduced models of helical anchors in sand, at the "French Institute of Science and Technology for Transport, Development and Networks" (IFSTTAR) in Nantes, France. More details of the experimental apparatus and methodology can be found in Tsuha et al. (2007).

2.1 *Model anchors*

Twelve different models of anchor were tested in two different samples of dry sand. These models were divided into two groups (with and without helical plates) to isolate the shaft resistance, Q_s, component from the total uplift capacity, Q_u, indicated in Figure 2. This figure illustrates the

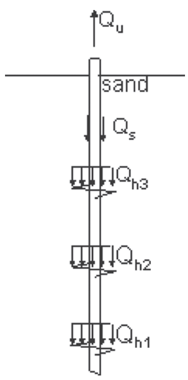

Figure 2. Resisting forces to the upward movement of a multi-helix anchor in sand.

hypothesis of the resisting forces to the upward movement of a multi-helix anchor embedded in sand. From this the hypothesis,

$$Q_u = Q_s + Q_h \qquad (1)$$

where Q_u is the helical anchor uplift capacity, Q_s is the shaft resistance, and Q_h is the uplift helix bearing capacity, which is expressed as:

$$Q_h = \sum_{i=1}^{N} Q_{hi} \qquad (2)$$

where Q_{hi} is the uplift bearing capacity of helix i, i is the index from 1 to N, and N is the number of helices.

The first group of anchor models is composed of nine different helical anchors (P1 to P9), made of 0.75 mm thick steel helical plates

Figure 3. Photography of the first group of model anchors.

(Fig. 3), with the inter-helix spacing of three times the helix diameter. The second group (P10 to P12) of three anchors without helical plates, were made of round steel bars of different diameters. The dimensions of the model anchors and the corresponding prototypes are presented in Table 1 and in Figure 4. The helices diameters of typical helical anchors range between 150 mm to 400 mm.

2.2 *Model soil*

The sand used to simulate the field soil in this study was the NE34 Fontainebleau silica sand. The sand samples were prepared by the air-pluviation in two containers (Table 2) with dimensions of 1200 × 800 mm in plan area and a height of 340 mm. The containers were filled with sand samples of different relative densities (I_D = 56% and 85%).

2.3 *Installation and loading testing*

A total of 24 tensile loading tests were carried out on the model anchors, twelve in the sand container 1, and twelve in the container 2. The model anchors were installed at three different depths as illustrated in Figure 4.

A servo-controlled test system (detailed in Tsuha et al., 2007) was used to install and to pull out the model anchors in the sand containers, in-flight at 22 g. The anchors were installed smoothly in sand at a rotation rate of 5.3 rpm. The bottom helix of all helical anchors was installed at a depth of 13.5 times the helix diameter (Fig. 4). After installation, the model anchors were pulled out vertically at a rate of 1 mm/s.

Table 1. Dimensions of model anchors (M) and prototype anchors (P).

Model anchor	No. of helices	Shaft diameter d_M (d_P) (mm)	Helix diameter D_M (D_P) (mm)	Helix pitch p_M (p_P) (mm)	Prototype pile tip depth (m)
P1	1	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1
P2	2	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1
P3	3	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1
P4	1	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6
P5	2	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6
P6	3	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6
P7	1	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2
P8	2	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2
P9	3	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2
P10	–	3.0 (64.3)	–	–	3.1
P11	–	4.5 (97.7)	–	–	4.6
P12	–	6.0 (132.0)	–	–	6.2

Notes: The anchor models were installed at different depths. Therefore, the g-levels were adjusted to extrapolate the dimensions of the anchor models to prototype values.

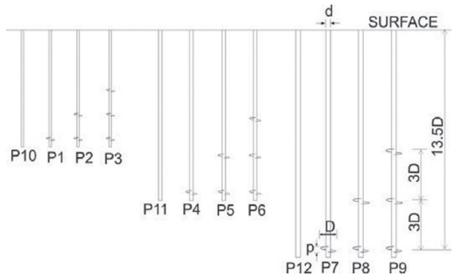

Figure 4. Model anchors used in Tsuha et al. (2007).

Table 2. Sand properties.

Property	Value
Maximum dry density (kN/m^3)	16.68
Minimum dry density (kN/m^3)	14.13
Effective size, D_{10} (mm)	0.20
D_{50} (mm)	0.30
D_{60} (mm)	0.32
Container 1	
Unit weight (kN/m^3)*	15.46
Density index (%)*	56
Peak friction angle ϕ (°)**	31
Container 2	
Unit weight (kN/m^3)*	16.30
Density index (%)*	85
Peak friction angle ϕ (°)**	41

*Estimated from calibrated boxes placed in the container.
**Measured from direct shear test.

3 CENTRIFUGE TESTING RESULTS

Table 3 shows the results of these pull-out tests in prototype values. In this table, the uplift helix bearing capacities Q_h of the tested anchors were calculated from the difference between the pull-out test results of anchors with (P1 to P9) and without helices (P10 to P12), for anchors with the same tip depth (see Fig. 4). The pile uplift capacity Q_u was taken as the peak load of the load-displacement curves.

Figure 5 shows examples of load-displacement curves of pull-out tests conducted on the model anchors of 326 mm helix (prototype) diameter, installed in the container 2 (denser container). The curves of the other loading tests carried out for this investigation are found in Tsuha et al. (2012).

3.1 *Efficiencies of the upper helices of multi-helix anchors*

The efficiency of an individual helix F_{Qhi} was evaluated in this study based on the measured fraction of uplift helix bearing capacity Q_{hi} for the helix i in relation to the total helix bearing capacity Q_h:

$$F_{Qhi} = \frac{Q_{hi}}{Q_h} \tag{3}$$

The uplift bearing capacities of the second helix (Q_{h2}) of the double-helix anchors were calculated by the difference between the Q_h results (Table 3) of double-helix and single-helix piles with the same helix diameter and tip depth (Fig. 4). The same procedure was employed to calculate the Q_{hi} fractions of middle and upper helical plates of triple-helix anchors.

In the present paper, only the efficiency of the second-helix (second from the bottom to the top of the anchor) is discussed.

The results of tests conducted on the anchor P2, with helix diameter of 214 mm, in the looser sand seems to be influenced by some local heterogeneity. For this reason, the contribution of the second helices of the anchors P2 and P3 installed in the container 1, was not verified in this paper.

Figure 6 illustrates the efficiencies of the second helix (F_{Qh2}), of double and triple-helix anchors. From this figure, it could be observed that the efficiency of the second helix depends linearly of the helix diameter, and also of the initial sand relative density (I_D).

3.2 *Effect of sand relative density*

Figure 6 shows that the initial relative density influences the efficiency of the second plate of multi-helix anchor installed in sand.

For dense sand, the difference in the final density between the sand penetrated by a helical plate one time and the sand penetrated two or three times is considerable. However, for the looser tested sand, after anchor installation, the final relative densities of the sand above the three helices are similar. This hypothesis, that explains the effect of sand density observed in Figures 6, is described in Figure 7.

The different shades of gray in Figure 7a identify two different groups of sand condition: initial density of the undisturbed sand, and the final density of a sand mass penetrated by helices. In Figure 7b, the different shades of gray correspond to four different groups of sand condition, which vary with the number of helical plates that penetrate through a particular zone of soil. This difference is caused by dilation in the dense sand increasing contact stresses, whilst in looser soil contraction results in a corresponding reduction in those stresses.

Table 3. Uplift helix bearing capacity results in prototype values (Tsuha et al. 2012).

Soil	Model pile	Helical plate diameter D_P (mm)	Nº of helical plates	Uplift helix bearing capacity Q_h (kN)
Container 1 ($I_D = 56\%$)	P1	214	1	14
	P2		2	19
	P3		3	43
	P4	326	1	46
	P5		2	83
	P6		3	112
	P7	440	1	69
	P8		2	108
	P9		3	150
Container 2 ($I_D = 85\%$)	P1	214	1	60
	P2		2	88
	P3		3	116
	P4	326	1	177
	P5		2	234
	P6		3	275
	P7	440	1	413
	P8		2	475
	P9		3	475

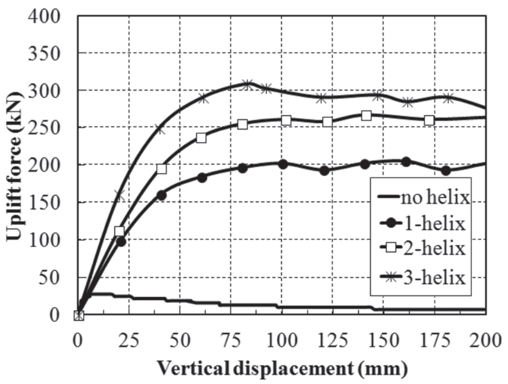

Figure 5. Load–displacement curves of tensile tests performed on model anchors of 326 mm helix (prototype) diameter in container 2.

3.3 *Effect of helix diameter on the efficiencies of the second plates*

The efficiencies of the second plates of the tested anchors decrease with the increase in helix diameter, as observed in Figure 6. This observation indicates that the effect of the helical anchor installation on the sand mass above the second helix is more important for helical piles with larger helices (larger second helices are less efficient). It means that the loss of capacity of the second helix compared to the bottom helix is greater for helical anchors with larger plates.

According to Tsuha et al. (2012), the region of disturbed sand around the cylinder circumscribed

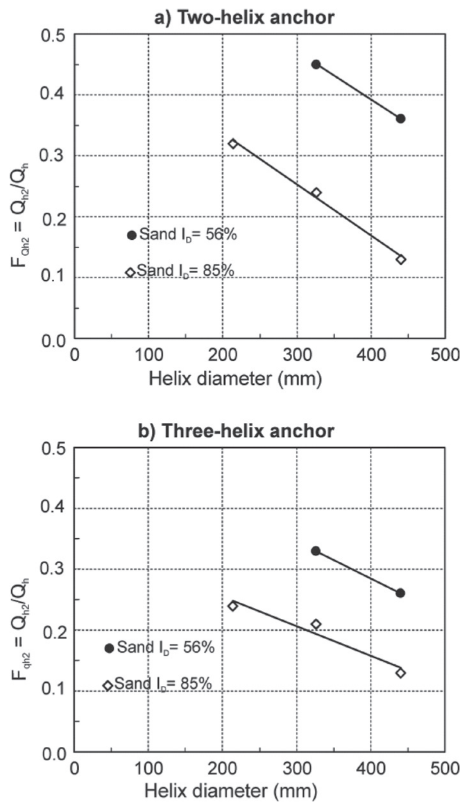

Figure 6. The variation of the second helix contribution to the total helix bearing capacity with helix diameter (Tsuha et al. 2012).

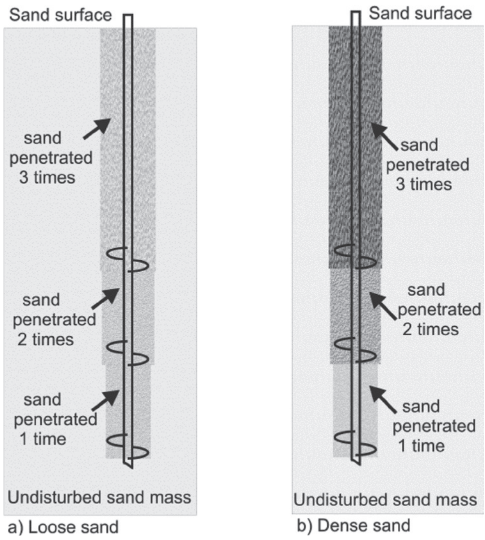

Figure 7. Hypothesis for sand disturbance after installation of a three-helix anchor: (a) loose sand; (b) dense sand (Tsuha et al. 2012).

by the helices after installation is larger for larger helix diameter. Consequently, for larger plate diameter, the cylindrical failure surface above the second helix, mobilized during the anchor loading, is horizontally more distant from the intact sand compared to the bottom helix of the anchor. This difference in the case of anchors with smaller plate diameter is less important.

3.4 *Effect of helix diameter on the dimensionless pull-out capacity factor N_{qu}*

The method to calculate the uplift capacity of helical anchors in sand, proposed by Mitsch & Clemence (1985), assumes that the bearing resistance of the top helix is estimated based on the the dimensionless pull-out capacity factor N_{qu}. They stated that the behaviour of the top helix in pull-out is similar to the end bearing of a deep foundation (for deep helical anchors). According to this method, the value of N_{qu} varies merely with the soil friction angle and with the embedment ratio (H/D, where H is the depth of the helix and D is the helix diameter). The dimensionless pull-out capacity factor N_{qu} for helical anchors is calculated by:

$$N_{qu} = \frac{Q_h}{\gamma' H A_h} \tag{4}$$

where γ' is the effective unit weight of the sand, and A_h is the projected area of the helix.

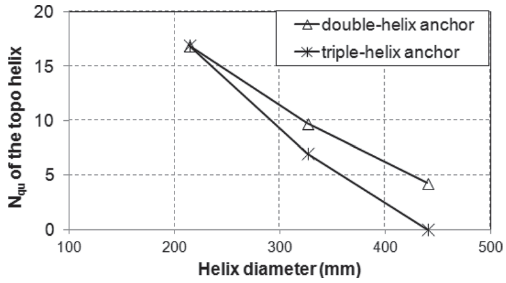

Figure 8. Variation of N_{qu} values of the top helices of double and triple-helix anchors with the helix diameter (denser sand).

In this investigation, as mentioned previously in this text, the uplift bearing capacities of the top helices Q_{hi} (of double–helix and triple-helix anchors) were determined. Therefore, the results of the N_{qu} of the top helices could be calculated by the Equation 4. Figure 8 illustrates the variation of the calculated N_{qu} values for the top helices with the helix diameter of the anchors tested in the container 2 ($I_D = 85\%$).

Figure 8 shows that N_{qu} values of the top helices, for helical anchors in sand with same soil friction angle and embedment ratio, decrease with the increase in helix diameter, as observed for the efficiencies results shown in Figure 6.

Further investigation is needed to confirm these findings. However, in an earlier investigation on helical piles based on full-scale load tests (Trofimenkov & Mariupolskii 1965), it was observed that in some cases (mainly in sand soils) in decreasing a pile plate diameter, an increase in the ultimate pressure was noticed, which is not taken into account in the methods of calculation. In this earlier work, these authors mentioned that the value of influence of the pile plate diameter on the ultimate pressure requires special study. Thus, the findings of the present centrifuge model study are compatible with this previously observed helix diameter effect by full-scale tests.

4 CONCLUSIONS

Centrifuge model tests have been conducted to investigate the effect of installation on the helical anchor performance in sand.

This paper reports some results of this experimental study, and an evaluation of the influence of sand relative density and helix diameter on the installation effect that affects the anchor capacity.

The results of these tests indicate that the efficiency of the second helix of helical anchors in sand decreases with the increase of the initial density of the sand and of the helix diameter.

The influence of the helix diameter was also observed on the dimensionless pull-out capacity factor of the top helices. This observation is important for the improving of the available methods to estimate the uplift capacity of helical anchors.

Future studies should be conducted to confirm the findings of this investigation.

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