Influence of multiple helix configuration on the uplift capacity of helical anchors

Influence de la configuration des hélices sur la résistance à l'arrachement de pieux hélicoïdaux

Tsuha C.H.C., Santos T.C.
University of São Paulo at São Carlos, Dept. of Geotechnical Engineering

Rault G., Thorel L., Garnier J.
Université Nantes Angers Le Mans, IFSTTAR, Centre de Nantes, Département GER, Physical Modelling in Geotechnics Group

ABSTRACT: The uplift capacity of multi-helix anchors usually depends on the helical blades configuration (including the number and the diameter) and the soil characteristics. An evaluation of those parameters is based on the results obtained from two different experimental programs. The first experiments were performed in centrifuge on dry Fontainebleau sand. For the second testing program, tension load tests were carried out in field at São Carlos in Brazil in a tropical soil. The geometrical effect (cylindrical or tapered helices) is also presented.

RÉSUMÉ : La capacité portante en traction des pieux hélicoïdaux dépend de la configuration des hélices (dont le nombre et le diamètre) et des propriétés du sol. Deux programmes expérimentaux permettent d'éclaircir l'influence relative de ces paramètres. L'un est réalisé sur modèles réduits centrifugés dans du sable sec de Fontainebleau, l'autre est mis en œuvre *in situ* sur un site test à Sao Carlos au Brésil, constitué de sols tropicaux. L'effet de la géométrie (hélices inscrites dans un cylindre ou dans un cône) est présenté.

KEYWORDS: helical anchor, tension capacity, centrifuge modeling, field load tests.

1 INTRODUCTION

Helical anchors have been employed in the construction of structures to sustain tension loads. Uses for helical anchors include transmission tower foundations, utility guy anchors, pipelines, braced excavations, retaining wall systems, etc. They are composed of helical bearing plates welded to a steel shaft, and installed into the ground by application of torsion to the upper end of the shaft (Figure 1).

The most common methods to estimate the uplift capacity of helical anchors are two: individual bearing and cylindrical shear methods. The individual bearing method assumes that the total capacity of a multi-helix anchor is equal to the sum of the individual capacities of each plate, estimated using the Terzaghi's (1943) general bearing capacity equation.

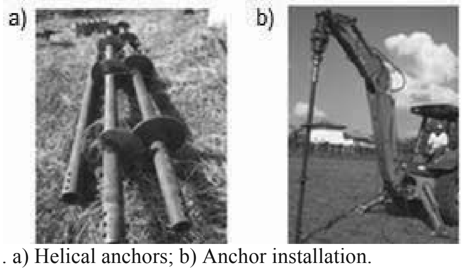

Figure 1. a) Helical anchors; b) Anchor installation.

The cylindrical shear method, described in Mitsch and Clemence (1985) and Mooney et al. (1985), supposes that the failure mechanism consisting of the bearing capacity failure above the top helix and of a cylindrical failure zone developed along the perimeter section between the helices.

The failure mechanism of helical anchors depends principally on the helix spacing ratio (ratio of helix spacing to helix diameter). Kulhawy (1985) stated that if the helices are widely spaced, the multi-helix anchor behaves as a sum of various single-helix anchors. According to the results of a field investigation on the behaviour of multi-helix anchors in clay, presented in Lutenegger (2009), there is no distinct transition from cylindrical shear to individual bearing behaviour. For helical anchors in sand, Lutenegger (2011) found that this transition occurs at a helix spacing ratio of about three.

For the application of these two prediction methods, used in helical anchor design, reductions in the values of some soil parameters have been suggested in the literature to consider the effect of the soil disturbance above the helices caused by the anchor installation.

As reported by Kulhawy (1985), significant disturbance does occur within the cylindrical installation zone of the helical anchor. Mitsch and Clemence (1985) cited that the installation of helical anchors induces significant stress changes in soil due to the disturbance produced by screwing the anchor into the sand and that these changes influence the anchor uplift behaviour.

Tsuha et al. (2012) mentioned that when a helical anchor is installed into the ground, the soil traversed by the helices is sheared and displaced laterally and vertically. According to these authors, the disturbance caused by the anchor installation is normally more pronounced in the soil above the upper plates than above the lower plates, because the upper soil layers are penetrated more times.

Some experimental investigations on helical anchors (Clemence et al. 1994, Sakr 2009, and Lutenneger 2011), with relative helix spacing of three times the plate diameter, have demonstrated 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 addition of one more plate is variable, and depends of the anchor configuration and soil characteristics.

For this reason, considering that a thorough understanding of the influence of helices configuration on the uplift behaviour of helical anchors is fundamental to give accurate estimates of the helical anchors capacity, the purpose of this paper is to evaluate the geometry effect on the soil disturbance due to anchor installation and its influence on the anchor capacity. Two different experimental programs were performed to this aim. Initially, centrifuge model experiments were carried out on scaled models of helical anchors with different dimensions in sand, at the "French Institute of Science and Technology for Transport, Development and Networks" (IFSTTAR) in Nantes, France, to investigate the variability of the rate of capacity gain due to the addition of one more helix to a helical anchor.

Considering that the use of helical anchors as tower foundation has being increased in Brazil, and tropical soils covers a significant part of the Brazilian territory, the second experimental program of the present investigation was carried out at a site of tropical soil, to evaluate the influence of the helical anchor configuration on the installation torque and on its uplift capacity.

2 EXPERIMENTS

2.1 Centrifuge testing modeling

A centrifuge model program was performed at the IFSTTAR, in France, to verify the influence of the diameter and number of helices on the multi-helix anchor uplift capacity in sand. The purpose of centrifuge modeling is to reproduce a full-scale response, with the possibility of comparisons between helical anchors with different dimensions, as the model anchors were installed in a uniform sand mass.

Nine small-scale anchor models (Figure 2; Table 1) were tested in two different samples of dry NE34 Fontainebleau silica sand (Table 2), with relative densities of 56% (container 1) and 85% (comtainer 2), respectively. The samples were prepared by the air-pluviation technique in two containers with dimensions of 1200 mm × 800 mm in plan area and a height of 340 mm.

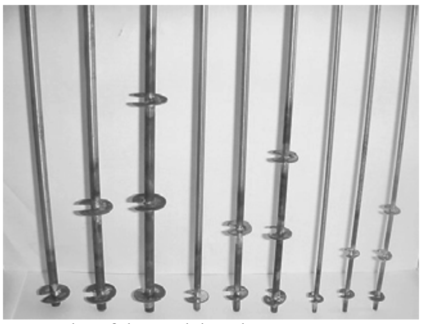

Figure 2. Photography of the model anchors.

For this investigation, tension load tests were performed on reduced-scale model piles, without helical plates (P10 to P12), to separate the shaft resistance, Q_s, from the total helical anchor uplift capacity, Q_u (see Figure 3 and 4). The cylindrical model anchors (multi-helix with same plate diameter), shown in Figure 2, were fabricated with the spacing between any two helices of three times the helix diameter.

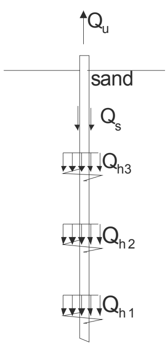

Figure 3. Resisting forces to upward movement of a multi-helix anchor in sand according to the " individual bearing" failure mechanism.

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

Pile	Nº of helix	Shaft diameter d_M (d_P) mm)	Helix diameter D_M (D_P) (mm)	Prototype tip depth (m)
P1	1	3.0(64.3)	10(214)	3.1
P2	2	3.0(64.3)	10(214)	3.1
P3	3	3.0(64.3)	10(214)	3.1
P4	1	4.5(97.7)	15(326)	4.6
P5	2	4.5(97.7)	15(326)	4.6
P6	3	4.5(97.7)	15(326)	4.6
P7	1	6.0(132)	20(440)	6.2
P8	2	6.0(132)	20(440)	6.2
P9	3	6.0(132)	20(440)	6.2
P10	-	3.0(64.3)	10(214)	3.1
P11	-	4.5(97.7)	15(326)	4.6
P12	-	6.0(132)	20(440)	6.2

Table 2. Sand properties.

Property	Value
Unit weight of soil particles (kN/m^3)	25.90
Maximum dry density (kN/m^3)	16.68
Minimum dry density (kN/m^3)	14.13
Maximum void radio	0.834
Minimum void radio	0.550
Maximum porosity	0.455
Minimum porosity	0.355
Container 1	
Unit weight (kN/m^3)	15.46
Density index (%)	56
Friction angle (º)	31
Container 2	
Unit weight (kN/m^3)	16.30
Density index (%)	85
Friction angle (º)	41

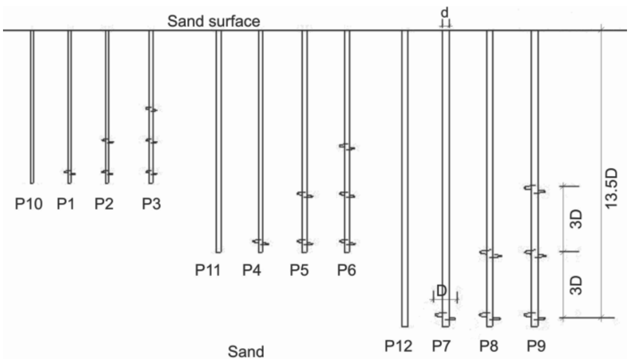

Figure 4. Model piles installed in the sand sample.

A total of 18 tensile loading tests were carried out on the model anchors, nine in the sand container 1, and nine in the container 2. The model anchors were installed at three different depths as illustrated in Figure 4. Further details of this experimental investigation are described in Tsuha et al. (2007).

2.1.1 Results of centrifuge tests

Figure 3 shows examples of load–displacement curves of tensile tests performed on the model anchors of 214mm helix (prototype) diameter, installed in the container 2 (denser sand). The curves of the other loading tests carried out for this investigation are presented in Tsuha et al. (2012).

From the results of this investigation, the fractions of the total helix bearing capacity (Q_h), related to each helical plate of the double-helix anchors ($F_{Qhi} = Q_{hi}/Q_h$, where Q_{hi} is the uplift helix bearing capacity of helix i), were calculated. The portion of helix bearing capacity related to the second helix (Qh_2) of the double-helix anchors was determined by the difference between the Q_h results of double-helix and single-helix anchors with same helix diameter and tip depth. A similar procedure was used to calculate the Q_h fractions of middle and upper helical plates of triple-helix anchors, and these results are included in Tsuha et al. (2012). Figure 4 shows the fractions of helix bearing capacity related to the second helix (F_{Qh2}) of the double and triple-helix anchors tested in this investigation.

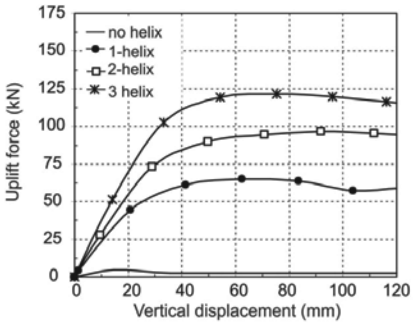

Figure 3. Load–displacement curves of tensile tests performed on model anchors of 214mm helix (prototype) diameter in container 2.

The results of tests performed on the model anchors with helix diameter of 214 mm in the looser sand are influenced by some local heterogeneity. For this reason, the contribution of the second helix of the anchors P2 installed in the container 1, was not shown in Figure 4.

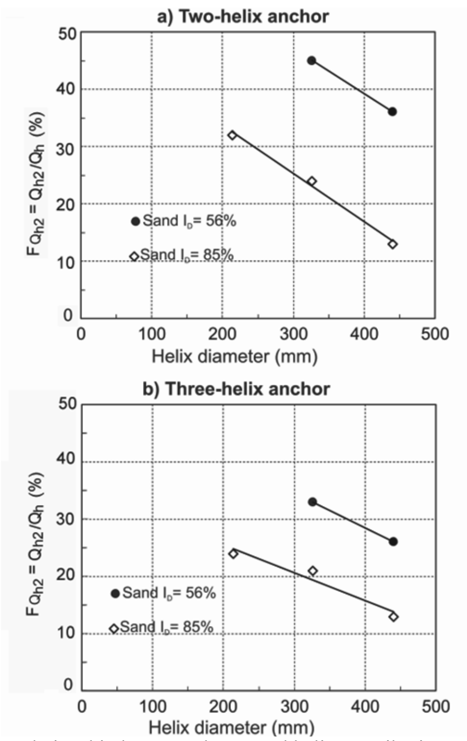

Figure 4. Relationship between the second helix contribution to total helix bearing capacity and the helix diameter of a) double helix and b) triple-helix anchors (Tsuha et al. 2012).

2.1.2 *Efficiency of the second helix*

Figures 4 shows that the efficiency of the second helix, of double and triple-helix anchors, depends linearly of the helix diameter, and also of the initial sand relative density (I_D).

2.1.3 *Effect of sand compactness*

The results of Figure 4 illustrate the influence of the relative density on the efficiency of the second plate of multi-helix anchors installed in sand. According to Tsuha et al. (2012), for dense sand, the difference in compactness between the sand penetrated by a helix one time and the sand penetrated two or three times is significant. Differently, for the looser tested sand, after anchor installation, the final relative densities of the sand above the three helices are similar. This hypothesis is detailed in Figure 5.

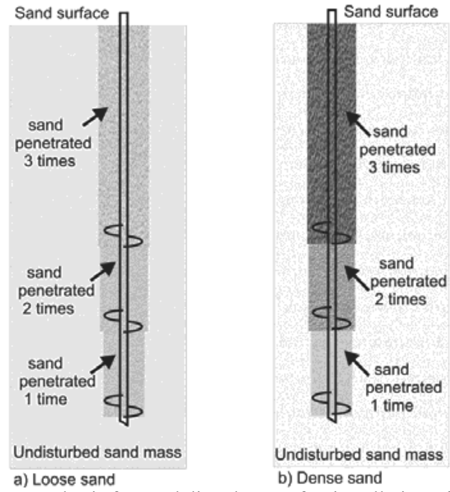

Figure 5. Hypothesis for sand disturbance after installation of a three-helix anchor: (a) loose sand; (b) dense sand (Tsuha et al. 2012).

2.1.4 *Effect of helix diameter*

The efficiencies of the second plates of the tested anchors decrease with the increase in helix diameter, as observed in Figure 4. This fact indicates that the effect of the helical anchor installation on the sand mass is more significant for helical anchors with larger plates. As the region of disturbed sand around the cylinder circumscribed by the anchors helices after installation is larger for larger helix diameter (increases with the helix diameter), the failure surface mobilized during the anchor loading is more distant from the undisturbed sand. Consequently, the efficiency of the second helix of cylindrical helical anchors decreases with the increase in diameter.

2.2 *Field testing program*

Eight helical anchors (Figure 6), with different configurations (multi-helix anchors with the same plate diameter and with increasingly larger diameter helices up the central shaft) were installed and tested at the CRHEA site of the São Carlos School of Engineering, São Carlos city, Brazil.

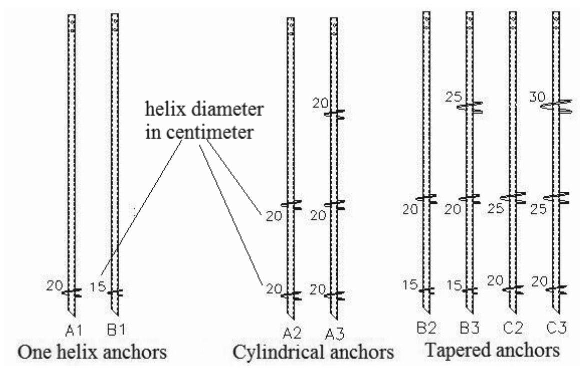

Figure 6. Prototype helical anchors tested at the CRHEA site.

The soil of the CRHEA site is material formed from igneous rock (basalt) from Serra Geral Formation (Figure 7). The top layer is a porous colluvial sandy clay with about 8 meters depth. Below this layer there is a residual soil (from igneous rock) limited by a thin layer of pebbles. The nature of this tropical soil is porous and has unstable structure due to the connections between particles by bonds attributed to soil water suction and cementing substances.

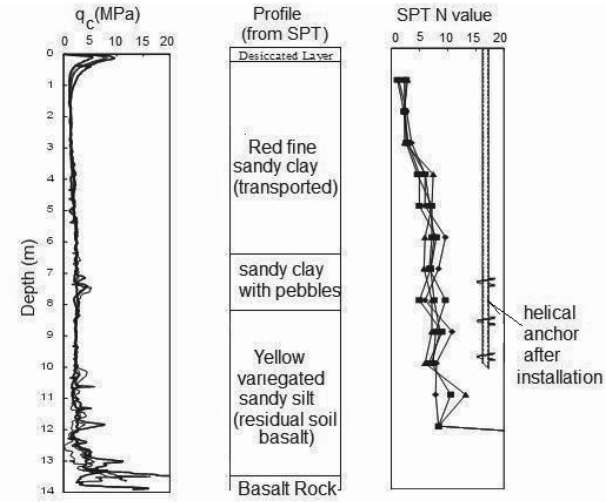

Figure 7. Soil profile at the CRHEA site.

2.2.1 *Results of field tests*

All anchors of this field investigation were installed with the anchor tip at a depth of 10 meters as illustrated in Figure 7. After installation, tension load tests were carried out on the anchors shown in Figure 6. More complete details of this investigation are available in Santos (2012).

The ultimate capacity (Q_u) of all tests was taken as the load producing a relative displacement of 10% of the helix average diameter. Table 3 presents the results of ultimate capacity (Q_u) of the tested anchors, and also the fractions of uplift capacity related the upper plates. Considering the homogeneity of this site, the fractions of uplift bearing capacity of the second plate of the multi-helix anchors (F_{Qh2}) were calculated by the difference between the ultimate capacity of anchors with two helices and of one helix (same bottom helix diameter). The fractions of uplift capacity due to the third plate (F_{Qh3}) of three-helix anchors were calculated by using the same procedure.

The comparison between the double-helix anchor A2 (cylindrical) and B2 (tapered) shows that the contribution of the second helix to the total capacity is better for tapered configuration. The second helix of the anchor B2 is larger than the bottom helix, and installed in a less disturbed soil layer compared to the second helix of the cylindrical anchor A2.

Table 3. Contribution of the upper plates to the total anchor uplift capacity.

Anchor	Helices diameters (mm)	Q_u (kN)	F_{Qh1} + Q_s fraction (%)	F_{Qh2} (%)	F_{Qh3} (%)
A1	200	14,5	100.0		
A2	200/200	25	58.0	42.0	
A3	200/200/200	36	40.3	29.2	30.6
B1	150	13,5	100.0		
B2	150/200	31	43.5	56.5	
B3	150/200/250	39	34.6	44.9	20.5
C2	200/250	48	30.2	69.8	
C3	200/250/300	57	25.4	58.8	15.8

However, from the comparison between the third helix contribution to the total capacity (F_{Qh3}) of three-helix anchors A3, B3, and C3, it could be observed that the efficiency of the third helix decreases with the third plate diameter, even for the tapered anchors. A similar trend was observed in the centrifuge tests presented in this paper. However, further investigation is needed to confirm this behaviour.

2.2.2 *Cylindrical and tapered helices*

The results of the final installation torque and the uplift capacity of helical anchors with same average plate diameter (A3 and B3) were compared. From this comparison it was found that the gain in uplift capacity for the tapered anchor is about 8%. However, to install the tapered model, it was necessary to apply a torque 20% larger than the needed to install the cylindrical model.

This difference is explained by the fact that during the tapered anchor installation, the upper helices pass through intact soil, differently of the upper helices of cylindrical anchor. However, during the loading of the both anchors, the both surfaces of soil mobilized above the plates are disturbed by the installation of the helices.

3 CONCLUSIONS

Two different types of experimental programs were carried on helical anchors to verify the effect of the helices configuration on the anchor uplift capacity. Based on the results of these tests, the most important conclusions are:

- The efficiency of the second helix of helical anchors in sand decrease with the increase of the relative density and the helix diameter.
- The uplift capacity of a triple-helix anchor with tapered helices is slightly superior then the one of cylindrical helices, with same average plate diameter in a tropical soil.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Clemence, S.P., Crouch, L.K., and Stephenson, R.W. 1994. Prediction of uplift capacity for helical anchors in sand. In Proceedings of the 2nd Geotechnical Engineering Conference, Egypt. Vol. I: 332–343.

Kulhawy, F.H. 1985. Uplift behaviour of shallow soil anchors — an overview. In Uplift Behaviour of Anchor Foundations in Soil. ASCE: 1–25.

Lutenegger, A.J. 2009. Cylindrical Shear or Plate Bearing? – Uplift Behavior of Multi-Helix Screw Anchors in Clay. Contemporary Issues in Deep Foundations, ASCE: 456-463.

Lutenneger, A.J. 2011. Behavior of multi-helix screw anchors in sand. *In Proceedings of the 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, Toronto, Ont. [CD ROM].

Mitsch, M.P., and Clemence, S.P. 1985. Uplift capacity of helix anchors in sand. In Uplift Behaviour of Anchor Foundations in Soil, ASCE: 26-47.

Mooney, J.S., Adamczak, S.J, and Clemence, S.P. 1985. Uplift Capacity of Helix Anchors in Clay and Silt. Uplift Behaviour of Anchor Foundations in Soil, ASCE: 48-72.

Sakr, M. 2009. Performance of helical piles in oil sand. *Canadian Geotechnical Journal* 46: 1046–1061.

Santos, T.C. 2012. The effect of helices configuration on the uplift capacity of helical piles in a tropical soil. Dissertation (master's degree) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos.

Terzaghi, K. 1943. *Theoretical soil mechanics*. John Wiley & Sons, New York.

Tsuha, C.H.C., Aoki, N., Rault, G., Thorel, L., and Garnier, J. 2007. Physical modeling of helical pile anchors. *International Journal of Physical Modelling in Geotechnics* 7(4): 1–12.

Tsuha, C.H.C., Aoki, N., Rault, G., Thorel, L., and Garnier, J. 2012. Evaluation of the efficiencies of helical anchor plates in sand by centrifuge model tests. *Canadian Geotechnical Journal* 49: 1102–1114.