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Evaluation of the Breakout Factor for Helical Anchors in Sand by Centrifuge Testing

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Abstract. The use of helical anchors has expanded in recent years although the understanding of its behavior is still unsatisfactory. The uplift capacity of multi-helix anchors in sand has been estimated using breakout factors, which vary with the sand friction angle and embedment ratio. These factors are affected by the disturbance produced by screwing the helices into the sand mass, which is more significant in the soil above the upper helices than above the bottom helix. However, the number and position of the helices (upper, intermediate or bottom) is not taken into account in the prediction of the uplift bearing capacity of the individual helices of helical anchors. The current investigation reports the effect of the number of helices on the breakout factor of helical anchors, measured from centrifuge tests in sand. Twenty-six tensile load tests were performed on different model anchors installed in sand samples with two different relative densities. The findings show that for helical anchors in dense sand, the values of breakout factor of the upper helices are lower compared to the bottom helix; however, for the looser sand case the values are similar.

Keywords. Helical anchor, centrifuge models, pull-out resistance, sand.

1. Introduction

Helical anchors, used to resist uplift forces, consist of one or more helical plates welded to a steel shaft. They are screwed into the soil by applying torque to the shaft. This type of anchor has been utilized extensively for both tensile and compressive applications for telecommunication towers, energy transmission and distribution lines, solar panel, and wind tower foundations. During the installation of a multi-helix anchor, the soil traversed by the helices experiences torsional and vertical shearing and is disturbed and displaced, mainly in a cylindrical volume with similar diameter to the helices. As cited in [1], during installation in sand, the soil that moves laterally transfers the stress to the surrounding soil, and at the same time, the limited overburden load allows upward movement of sand, and it may cause loosening effect. Consequently, after installation the properties of the soil inside the cylinder above the helices are modified. In the case of multi-helix anchors, the soil inside the cylindrical zone above the upper helices is penetrated more times than the soil above the bottom helix. Therefore, for a multi-helix anchor, with all helices

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installed in a uniform soil, the strength characteristics of the soil above the bottom and above the upper helices should be different.

On the other side, the methods to calculate the pull-out capacity of helical anchors are expressed in terms of non-dimensional breakout factors that are independent of the position of the load-bearing helix (first or bottom helix, second, third, fourth, etc.) in relation to the anchor tip. However, the estimate of the reduction in these factors, according to the disturbance effect of anchor installation, is essential to the prediction of the uplift capacity of helical anchors. In order to redress this deficiency, an experimental research was carried out to evaluate the non-dimensional breakout factor of deep helical anchors in sand. For this investigation, several pull-out tests have been performed on different models of anchor, with different number and diameter of helices, installed in sand samples of different relative densities (I_D) in a centrifuge. The field self-weigh-induced stresses in a reduced-scale model can be reached from the high gravitational acceleration field produced by a geotechnical centrifuge. This technique is capable of providing the stress-strain distributions similar to the full-scale condition.

2. Non-dimensional breakout factor for helical anchors in sand

The work of [2] was the first to present a formula which expresses the uplift bearing capacity of a helical plate as a function of non-dimensional factors (similar to Terzaghi's bearing capacity equation). Later, [3] have been conducted a number of uplift tests on multi-helix anchors installed in different soils. These authors assumed that each helix behaved independently of the other, because the helices were widely spaced. Consequently, the uplift capacity of the multi-helix anchor is the summation of the bearing capacities of all helical plates and the shaft resistance. Therefore, they use the following bearing capacity expression to calculate the uplift resistance of each helical plate in sandy soil:

$$Q_h = \gamma' H \, N_{qu} A_h \quad (1)$$

where Q_h = helix bearing capacity (kN), γ' = effective unit weight of the soil (kN/m^3), H = depth of the helix (m), N_{qu} = breakout factor, which depends on the angle of friction and relative density of the soil, A_h = projected area of the helix (m^2).

3. Centrifuge testing

The current work is based on the results of centrifuge model tests performed on three different containers, filled with dry sand. Two previous investigations [4, 5] were based on the results of the tests performed in two of these three containers. The purpose of the current paper is to complement the previous works by evaluating the variation of the non-dimensional breakout factors with the number and diameter of helices, and relative embedment depth (H/D, where H is the helix depth, and D is the helix diameter) to improve the current estimate of the uplift capacity of helical anchors.

The uplift tests on reduced scale model anchors was carried out using the geotechnical centrifuge of the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) in Nantes, France. Sixteen different small-scale anchor models were tested (Table 1) in three containers, with dimensions of 1200 mm × 800 mm × 340 mm, filled with dry NE34 Fontainebleau silica sand (Table 2), prepared by the air-pluviation technique. The containers were filled with sand samples of different relative densities: container 1 with sand I_D of 56%, and containers 2 and 3 with sand I_D of 85%.The properties of the three samples are described in Table 2.

To separate the portion of anchor uplift capacity related to shaft resistance from the portion related to the bearing capacities of the helical plates, two different sets of model anchors (Table 1) were fabricated (eleven with and five without helical plates) to subtract the shaft resistance (Q_s) from the total uplift capacity (Q_u). However, the results of shaft resistance (Q_s) measured in this experimental program do not represent prototype piles, because of the possibility of scale effects. As reported in [6], for small piles with a diameter much smaller than 100 times the soil average grain size (100 d_{50}), the mobilized shear strength are two to three times the value observed on large piles. In the present experiments, the shaft diameters are 10 to 20 d_{50}. Therefore, the results of shaft resistance (Q_s) obtained from the tests on the anchors without helix (P10, P11, P12, P10', and P11') are only usable to separate the portion of the helix bearing capacity (Q_h) from the total uplift capacity (Q_u) of the tested helical anchors. Possible scale effects in the results of centrifuge model tests on helical piles are discussed in [7].

Table 1. Model (M) and corresponding prototype (P) dimensions of the tested anchors.

Model anchor		No. of helices	Shaft diam. dM (dP) (mm)	Helix diam. DM (DP) (mm)	Pitch pM (pP) (mm)	Prototype anchor tip depth (m)	Embedment ratio of the top helix(H_{top}/D)
With helices	P1	1	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1	13.5
	P2	2	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1	10.5
	P3	3	3.0 (64.3)	10 (214)	3.0 (64.3)	3.1	7.5
	P4	1	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6	13.5
	P5	2	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6	10.5
	P6	3	4.5 (97.7)	15 (326)	3.2 (69.5)	4.6	7.5
	P7	1	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2	13.5
	P8	2	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2	10.5
	P9	3	6.0 (132.0)	20 (440)	3.5 (77.0)	6.2	7.5
	P1	1	3.0 (66.0)	10 (220)	3.0 (66.0)	6.2	27.0
	P4	1	4.5 (99.0)	15 (330)	3.2 (70.4)	6.2	18.0
No helix	P1	-	3.0 (64.3)	-	-	3.1	-
	P1	-	4.5 (97.7)	-	-	4.6	-
	P1	-	6.0 (132.0)	-	-	6.2	-
	P1	-	3.0 (64.3)	-	-	6.2	-
	P1	-	4.5 (97.7)	-	-	6.2	-

Note: To transform the dimensions of the models to prototype values, the following g-levels were adopted: 21.44 *g* for anchors 1,2,3 and 10; 21.71 *g* for anchors 4,5,6 and 11; and 22 *g* for anchors 7,8,9,12,1',4', 10', and 11'.

Figure 1 presents the model anchors P1 to P9 (Table 1), fabricated with different number and diameter of helices. Three different helix plate diameters (Figure 1) were tested in the current work. However, as in the case of the looser sand container (I_D = 56%) the results of the models of smaller helix diameter (P1, P2, and P3) are not accurate because of the scaling effect, only two different helix diameters were evaluated. A total of 26 tensile loading tests were carried out: 8 tests in Container 1, 12 tests in Container 2, and 6 tests in the Container 3 (Figure 2). A servo-controlled test system, described in [8], was used to installation and testing on the model anchors in sand containers, in-flight at 22 *g*. The model anchors were installed at a rotation rate of 5.3 rpm. The displacement of the anchor tip, and the axial load were monitored by displacement and force transducers. After installation, the anchors were pulled out vertically at a rate of 1 mm/s. Further test details are described in [9].

In Containers 1 and 2, the lower helices of the anchors were installed to a depth of 13.5 times the plate diameter (Figure 2). Consequently, the embedment ratio (*H*/*D*) of the top helices is the same for all anchors of same number of helices, and different plate diameter. In this case, the top helices of the double and triple-helix anchors were installed at embedment ratios of 10.5*D* and 7.5*D*, respectively. In Container 3, helices of different diameter were installed at the same depth, and different embedment ratios (from 13.5*D* to 27*D*), as shown in Figure 2b. The aim of these tests was to compare the breakout factor values for helical plates of different diameters installed at the same depth.

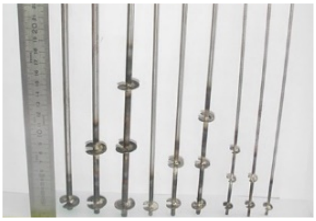

Figure 1. Anchor models P1 to P9 used in the centrifuge tests.

Table 2. Properties of model ground.

Fontainebleau sand (NE34)		Value
Mean grain size, d_{50} (mm)		0.30
Uniformity coefficient, C_U		1.88
Maximum void radio, e_{max}		0.834
Minimum void radio, e_{min}		0.550
Density of solid particles, ρ_s (g/cm^3)		2.64
Maximum dry density, $\rho_{d\,max}$ (g/cm^3)		1.70
Minimum dry density, $\rho_{d\,min}$ (g/cm^3)		1.44
	Container 1	Containers 2 and 3
Unit weight, γ (kN/m^3)	15.46	16.30
Relative density, I_D (%)	56	85
Friction angle, ϕ (°)	31	41

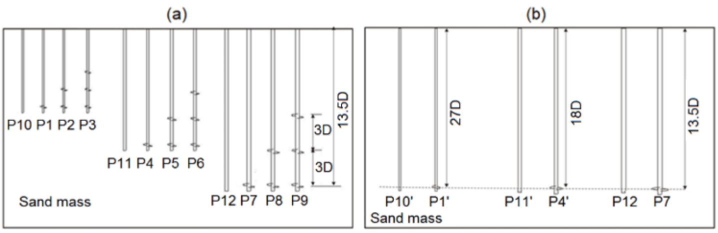

Figure 2. Final embedded depth of the model anchors installed in: a) Containers 1 and; b) Container 3.

4. Results and discussion

In this study it was assumed that the individual helices of the multi-helix anchors act independently of each other (inter-helix space = 3*D*). This assumption for sandy soils, agrees with previous works [3, 9, 10, and 11]. Therefore, the total capacity of the helical anchors, Q_u, is the sum of the shaft resistance, Q_s, and of the individual capacities of each helix, Q_{hi}:

$$Q_u = Q_s + \sum_{i=1}^{N} Q_{hi} \tag{2}$$

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

The values of the uplift capacity (peak uplift load of the load–displacement curves) of 26 tested anchors, installed in three containers, are presented in Table 3. The curves of the tensile load tests carried out in the Containers 1 and 2 are available in [5], and the curves of the tests in the Container 3 are illustrated in Figure 3. The aim of this study is to evaluate separately the uplift capacity of the helical plates, and then it is essential to isolate the portion related to the bearing capacities of the helices (Q_h) in the results from the total uplift capacity (Q_u). Although the shaft resistance is not significant in this study compared with the helix contribution to the uplift capacity, two different assumptions (A1 and A2) were used to estimate Q_s (Table 3). These assumptions represent an upper and a lower limit for the resistance offered by the shaft.

Table 3. Uplift helix bearing capacity (Q_h) results in prototype values.

Soil	Model anchor		Helix Diam (mm)	N° of helices	Uplift capacity Q_u (kN)	Uplift helix bearing capacity Q_h (kN)	
						Assumption 1	Assumption 2
Container 1 (I_D =56%)	Helical anchor	P4	326	1	46	-	46
		P5	326	2	83	-	83
		P6	326	3	112	-	112
		P7	440	1	74	-	74
		P8	440	2	113	-	113
		P9	440	3	155	-	155
	No helix	P11	-	-	0	-	-
		P12	-	-	5	-	-
Container 2 (I_D =85%)	Helical anchor	P1	214	1	66	60	66
		P2	214	2	94	88	94
		P3	214	3	122	116	122
		P4	326	1	204	177	204
		P5	326	2	261	234	261
		P6	326	3	302	275	302
		P7	440	1	494	413	494
		P8	440	2	556	475	556
		P9	440	3	556	475	556
	No helix	P10	-	-	6	-	-
		P11	-	-	27	-	-
		P12	-	-	81	-	-
Container 3 (I_D =85%)	Helical anchor	P1'	220	1	221	206	221
		P4'	330	1	326	248	326
		P7	440	1	503	414	503
	No helix	P10'	-	-	15	-	-
		P11'	-	-	78	-	-
		P12	-	-		6.2	-

In the first assumption (A1), used in [4] and in [5], the results of Q_u obtained from the uplift tests on the anchors without helices (P10 to P12) are equivalent to the shaft resistance of the helical anchors with the tip installed at the same depth (see Figure 2a). In this case, the shaft resistance is mobilized along the shaft length (also between the helices), and it was supposed that the shaft resistance is not affected by the previous penetration of the helix. For the second assumption (A2), the shaft resistance of the helical anchors is neglected. Therefore, the measured result of anchor uplift capacity (Q_u) is assumed to be equal to the helix bearing capacity (Q_h). This hypothesis is consistent with the known effect of helices installation on the soil around the shaft ([12]). As shown in Table 3, the values of uplift capacity of the anchors without helices installed in the Container 1 ($I_D = 56\%$) are irrelevant. Therefore, to obtain the results of Q_h of the helical anchors installed in the looser sand container, it was only assumed the condition A2.

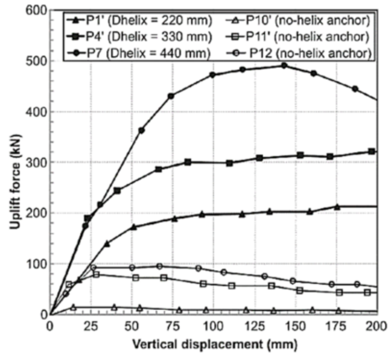

Figure 3. Load–displacement curves of uplift loading tests performed in Container 3 ($I_D = 85\%$).

The investigation on the performance of single-helix anchors is a prerequisite to the understanding of the behaviour of the bottom helical plate of multi-helix anchors, when the inter-helix space is enough to provide the anchor condition equivalent to a sum of independent single anchors. For evaluating the influence of the helix diameter on the helical anchor behaviour in sand, two different conditions were verified. First, it was compared the influence of the plate diameter on the breakout factor of the helical plates installed at the same depth (Container 3). In the second evaluation, the helices of different diameters were installed at the same embedment ratio (13.5D), because according to the previous researches, for a given sand friction angle, the helical plates installed at the same embedment ratio should provide the same value of breakout factor.

Figure 4 shows the results of ultimate pressure and breakout factor of the single-helix anchors in dense sand. Figure 4a illustrates that for helices installed at the same depth, the ultimate pressure shows a tendency to decrease in increasing the helix diameter, and consequently decreasing embedment ratio. In Figure 4b, for the both cases evaluated (plates at the same depth, and at the same embedment ratio) the breakout factor decreases with the helix diameter. However, this reduction is more important in the comparison between helices at the same depth. In this case, the embedment ratio (H/D) of the smaller helix is greater compared to the case of larger helices, and as observed by different authors in literature N_{qu} should increase with embedment ratio.

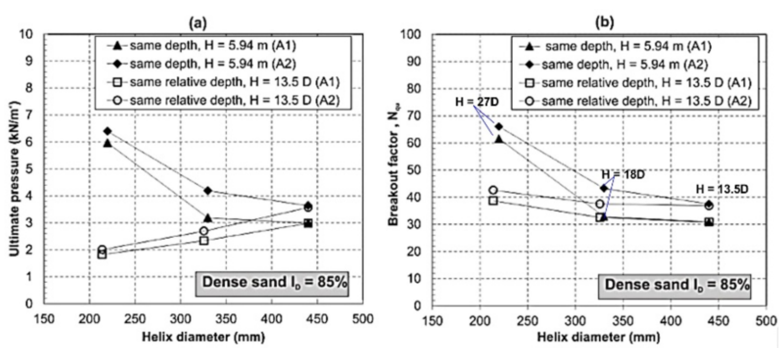

Figure 4. Ultimate pressure and breakout factor of the single-helix anchors in the Containers 2 and 3.

Figure 5 presents a comparison between the results of helical anchors with different diameters installed in dense and medium dense sand. Figure 5a shows that, for a given embedment ratio, the ultimate pressure of helical plates in dense sand increases with plate diameter (the level of confining pressure is more important for the larger helices). However, for the anchors in the looser sand container the ultimate pressure is slightly reduced with the increase of the plate diameter. Figure 5b illustrates that as observed for single-helix anchors in dense sand, the breakout factor of the helical plates in the looser sand slightly decreases with the increase of plate diameter.

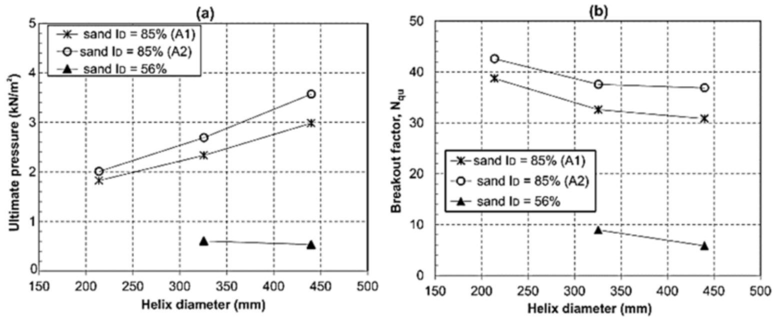

Figure 5. Ultimate pressure and breakout factor of the single-helix anchors installed at the same relative depth $H = 13.5D$ in Containers 1 ($I_D = 56\%$) and 2 ($I_D = 85\%$).

The effect of the soil disturbance on the breakout factors of multi-helix anchors was evaluated via comparison between the average ultimate pressure and breakout factor results obtained for single-helix and multi-helix anchors. The results of the average ultimate pressure and breakout factor (N_{qu}) are presented in Figure 6. The effect of helix diameter on the results was evaluated for anchors with the same embedment ratio and number of helices, installed in dense and medium dense sand. As the projected area of the helix (A_h) is the same for all helices of a multi-helix anchor of this study, the average breakout factor for multi-helix anchors was calculated by substituting the Eq. (1) into Eq. (2):

$$N_{qu} = \frac{Q_h}{\gamma' . A_h \sum_1^N H_i} \quad (3)$$

Figure 6a shows that the ultimate pressure of the single-helix anchor in dense sand, for the three tested helix diameters, is much higher than the average ultimate pressure obtained from the tests on the double and triple-helix anchors. Also, the values for double-helix anchors are greater than for triple-helix anchors. These results indicate that the disturbance in the dense sand, caused by the installation of the helical plates, is more important above the upper plates. This occurs because the degree of sand loosening increases with the number of helical plates that penetrate a particular sand layer. Differently, in the case of helical anchors in the looser sand, the number of helices does not influence the average ultimate pressure and breakout factor values. It occurs because after the penetration of the first helix of a multi-helix anchor, the sand inside the cylinder circumscribed by the helix becomes practically loose. Consequently, after penetration of the second and third helices, the sand above the second and third plate does not change considerably.

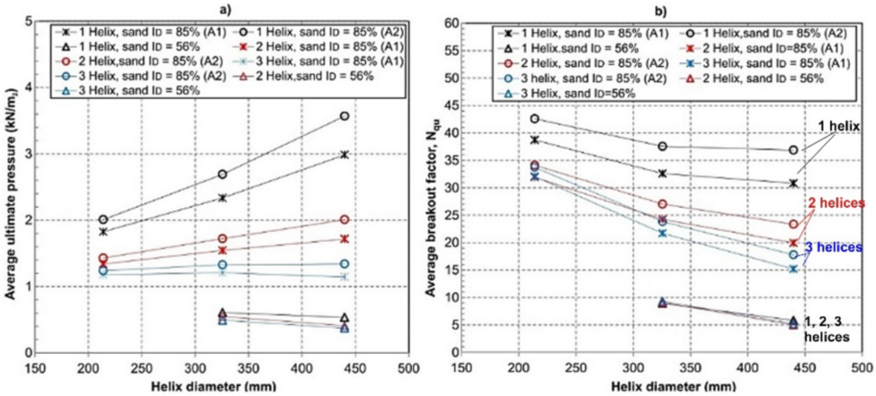

Figure 6. Average ultimate pressure and breakout factor of the helical anchors in containers 1 and 2.

5. Conclusions

A series of centrifuge model tests were conducted to investigate the behavior of multi-helix anchors in sand. The results indicate that the breakout factor of multi-helix anchors in dense sand decreases with the number of helices. On the other hand, in the case of anchors in looser sand, the value of breakout factor is not influenced by the number of helices. This observation indicates that the installation effect on the individual uplift capacities of the helical plates depends on the initial compactness of the sand.

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