Behavior of Multi-Helix Screw Anchors in Sand

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ABSTRACT
The behavior of multi-helix screw anchors in sand was investigated by performing a series of full scale axial uplift (pullout) tests on square-shaft screw-anchors. The load tests were conducted until a deformation of at least 20% of the diameter of the largest helical plate was achieved. Tests were performed on double-helix and triple-helix cylindrical screw anchors with helix spacing to diameter ratios varying from 0.75 to 3.0. A set of tests was also performed at a fixed helix spacing of 1.5 with the number of helices varying from 1 to 4 to evaluate efficiency. The results are compared with commercially available triple-helix screw anchors that have the helix diameter increasing up the shaft. The results of the tests are used to illustrate the difference in ultimate capacity for the different geometry anchors.

RÉSUMÉ
Le comportement des ancres de vis de multi-spirale en sable a été étudié en réalisant une série d'essais axiaux complets de soulèvement (dégagement) sur des vis-ancres de place-axe. Les essais de charge ont été effectués jusqu'à ce qu'une déformation au moins de 20% du diamètre du plus grand plat hélicoïdal ait été réalisée. Des essais ont été réalisés sur les ancres cylindrique de double-spirale et de vis de triple-spirale avec la spirale espaçant aux rapports de diamètre variant de 0.75 à 3.0. Un ensemble d'essais a été également réalisé à un espacement fixe de spirale de 1.5 avec le nombre de spirales variant de 1 à 4 pour évaluer l'efficacité. Les résultats sont comparés aux ancres disponibles dans le commerce de vis de triple-spirale qui ont le diamètre de spirale augmenter vers le haut de l'axe. Les résultats des essais sont employés pour illustrer la différence dans la capacité finale pour les différentes ancres de la géométrie.

1 INTRODUCTION

Helical anchors have been used for the past 170 years to resist uplift loading for a variety of applications involving a wide range of soil conditions (Lutenegger 2011). While a helical anchor is used in much the same way as a grouted anchor is used, the development of tension capacity is very different between these two types of ground anchors. A helical anchor is installed as a direct embedment plate anchor without a borehole and derives capacity from one or more helical plates that have been installed by rotation of a central shaft. Both the helical plates and central shaft are a part of the structural unit and remain in place.

In design, the engineer has a number of options to consider in selecting a helical anchor for a particular project. The engineer may select a single-helix or a multi-helix anchor. If a multi-helix anchor is selected the choice usually becomes one of selecting either a double-helix or a triple-helix anchor and whether to select a multi-helix anchor with the same diameter helical plates or, as some manufacturers provide, a multi-helix with increasingly larger diameter helices up the central shaft, i.e., a "tapered" anchor. The performance and load capacity of helical anchors depends on the specific geometry of the anchor, i.e., size, pitch and number of helices, the size and shape of the central shaft, the depth of embedment and the soil conditions at the site. Additionally, some consideration regarding the degree of disturbance to the soil may be taken into account as well.

Many manufacturers of screw-piles and helical anchors produce standard multi-helix elements with a relative helix spacing of 3 times the plate diameter and suggest that at this spacing, the plates act independently of each other so that the total capacity of a multi-helix anchor is generally assumed to be equal to the sum of the individual capacities of each plate:

$$Q_{MU} = \Sigma Q_{IU}$$

where:
Q_{MU} = Ultimate Uplift Capacity of a Multi-Helix Anchor
Q_{IU} = Ultimate Uplift Capacity of an Individual Single-Helix Anchor

However, there is very little data published from full-scale field tests in which this assumption has been clearly demonstrated for either sands or clays. Based on the limited data available for sands (e.g., Clemence et al. 1994; Sakr 2009; Tsuha & Aoki 2010), it appears that even at a spacing of 3 plate diameters the individual plates may not act independently. The Efficiency of a multi-helix anchor should be considered very different from the Efficiency of a pile group or footing group or a group of single helical anchors simply because the plates are stacked along the same central shaft in contrast to being located adjacent to each other in a row or square pattern with a clear horizontal distance between elements.

In this study, different sizes of single- and multi-helix screw anchors of the same diameter were installed in a natural sand and load tested to failure in axial tension. The tests were conducted to evaluate the Efficiency of multi-helix screw anchors over a single-helix anchor of the same diameter. In addition to investigating the influence of plate spacing to determine if or when a transition to Individual Plate behavior occurs, there is also a very practical reason to understand the behavior of multi-helix anchors with close spacing. In real projects there are certain occasions when a multi-helix anchor with large spacing cannot be embedded in a single stratum, simply because the anchor is too long for all plates to fully engage the same soil layer to develop capacity. In these situations, the Engineer may elect to use a multi-helix anchor with a closer helix configuration in order to engage a specific soil layer for developing anchor capacity. When this occurs, the engineer needs to have an understanding of how that capacity is developed..

2 DESIGN OF DEEP MULTI-HELIX SCREW ANCHORS

There are two design approaches to determine the ultimate tension (uplift) capacity of deep multi-helix screw anchors based on soil mechanics that can be considered; 1) Individual Plate Method, and 2) Cylindrical Shear Method. Both methods require some simplifying assumptions in order to determine the ultimate capacity. Based on deep bearing capacity theory the zone of the failure surface above or below a plate should be related to the effective stress drained friction angle of the sand, φ'.

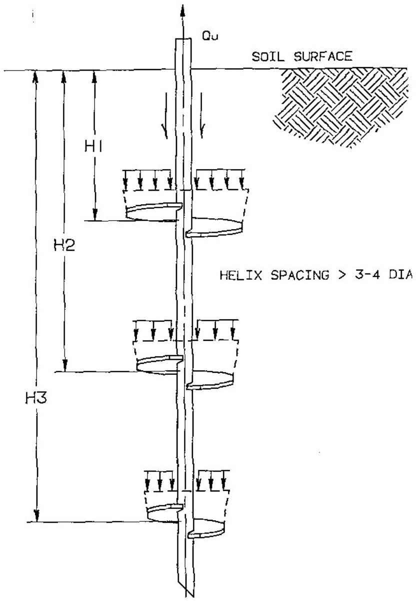


Figure 1a. Individual Plate Behavior.

2.1 Individual Plate Method

The Individual Plate Method assumes that individual bearing failures occur simultaneously above each helix as shown in Figure 1a. As a result, the uplift capacity of the anchors is simply equal to the sum of the resistance in uplift of each plate. For deep anchor installation (i.e., top helix greater than about 8 diameters below ground surface) the failure is similar to end bearing of deep foundations. Generally, the Individual Plate Method is applicable to anchors with large plate spacing.

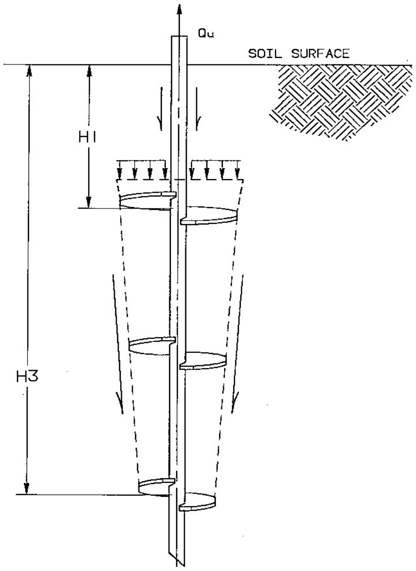


Figure 1b. Cylindrical Shear Behavior.

2.2 Cylindrical Shear Method

In the Cylindrical Shear Method of analysis, it is assumed that the soil in between the helices acts as a semi-rigid body and that a cylindrical or tapered failure zone develops along the perimeter section jointed between the helices as shown in Figure 1b. In uplift, there would also be plate bearing resistance from the upper most plate, so in effect this method is actually a combination of cylindrical shear (between plates) and plate bearing (top plate). The Cylindrical Shear Method is considered to be more applicable to anchors with close plate spacing.

Design equations for calculating the ultimate uplift capacity in sands for both methods have been presented by previous investigators (e.g., Mitsch and Clemence 1985; Das 1990). The transition from Cylindrical Shear to Individual Plate behavior occurs at a relative spacing of about 2.5 for clays. In sands, the suggestion has been made that this transition occurs at about a relative plate spacing of 3, however, there are essentially no published data to confirm this assumption. Both analyses rely on an accurate determination of the mobilized soil friction angle φ' in order to calculate the ultimate uplift capacity.

For both single-helix and multi-helix anchors, the installation may have some influence on the soil as some disturbance must take place simply to advance the anchor. The degree of disturbance is unknown and may be dependent on the skill of the equipment operator and other factors such as initial relative density, in the case of sand. Initially, for the current study, the discussion of the results did not consider soil disturbance. One way to evaluate the behavior of multi-helix anchors with different plate spacing or with different numbers of plates of constant spacing is to think in terms of the Efficiency of a multi-helix anchor as compared to a single-helix anchor of the same diameter. This is similar to the Efficiency of Pile Groups, except of course in this case, the individual foundation elements are stacked vertically along a central shaft.

3. INVESTIGATION

3.1 Site Description

The test site is located at the University of Massachusetts Agricultural Farm in South Deerfield, Ma. adjacent to the Connecticut River. The site consists of a thin surficial layer of sandy silt (average fines content = 56.0%) which extends to a depth of about 1.2 m (4 ft.) overlying a 3.5 m (11.5 ft.) thick layer of sand that extends to a depth of 4.7 m (15.5 ft.). The sand is underlain by lacustrine clay that is stiff in the upper 2 m (6 ft.) but grades quickly into soft consistency and extends to about 12.2 m (40 ft.). The water table at the site is generally perched at the top of the clay. The upper silt and sand are moist and partially saturated. The sand is relatively uniform medium to coarse sand with average mean grain diameter, D_{50} = 0.6 mm and average Uniformity Coefficient, C_c = 1.6. Average total unit weight of the sandy silt and sand were estimated to be 1.58 Mg/m^3 (98.6 lbs/ft^3) and 2.0 Mg/m^3 (124.8 lbs/ft^3), respectively. Standard Penetration Tests in the upper 7.6 m (25 ft.) range from N_{60} = 8 – 22. Results of four Borehole Shear Tests performed in the sand between depths of 2 to 4 m (6.5 to 12 ft.) gave average values of φ' = 33.5^0 and c' = 0 kPa.

3.2 Field Load Tests

Full-scale field loading tests were performed in order to evaluate the behavior of multi-helix anchors in sand. Several multi-helix anchors were fabricated using a constant diameter helical plate to provide "cylindrical" anchors with a range in helix spacing. Series-1 consisted of a single 203 mm (8 in.) helical anchor and six multi-helix anchors consisting of three 100 mm (8 in.) diameter helices with a helix pitch of 76 mm (3 in.) and relative spacings of s/D = 0.75; 1.125; 1.5; 2.25; 3; and 4.125. Series-2 consisted of a single 203 mm (8 in.) helical anchor and double- triple- and quadruple-helix anchors with relative spacings of 1.5 and 3.0. Two additional commercially manufactured multi-helix "tapered" anchors with helix diameters of 150 mm (6 in.), 203 mm (8 in.) and 254 mm (10 in.) and relative spacings of 1.5 and 3.0 were tested. A square 38 mm x 38 mm (1.5 in. x 1.5 in.) steel central shaft was used on all anchors.

In the current study, all helical anchor tests were performed with the anchors fully embedded in the sand layer. Anchors were installed with the center of the lead helical section at a depth of 3.0 m (10 ft.) in order to represent average soil conditions and vertical effective stress through the helical section. In the case of single-helix anchors, the helix was located at a depth of 3 m (10 ft.). All anchor plates are considered sufficiently embedded to act as deep anchors. While it would have been desirable to test larger helix spacings, say up to 4.5 or larger, this was not considered practical for the site conditions.

3.3 Load Test Procedure

Load tests were performed using the incremental maintained load (ML) method using the general procedures described in ASTM D3689 *Standard Test Method for Individual Piles Under Static Axial Tensile Load*. Load was applied by a single acting hollow ram 250kN hydraulic jack placed on top of two reaction beams centered over the anchor and resting on wood cribbing. Load was transferred from the jack to the anchor using a threaded rod. The load was measured using a Geokon donut load cell placed over the threaded rod on top of the hydraulic jack and was read using an electronic digital indicator. Deformation measurements were made using two digital dial indicators with a resolution of 0.0127 mm (0.0005 in.) attached to an independent reference beam and placed equidistant on opposite sides of the anchor. The dial indicators were referenced to a steel plate threaded to the top of the anchor. Loads were applied incrementally in the range of approximately 5 to 10% of the estimated ultimate capacity of each anchor. Loads were applied until a relative displacement of 20% of the plate diameter was achieved or the anchors failed by rapid pull-out, whichever occurred first.

4 RESULTS

4.1 Ultimate Capacity

Tables 1 and 2 provide a summary of the test results for Series-1 and Series-2, respectively. The measured loads at relative displacements of 5%, 10% and 20% of the plate diameter are given and designated Q_5, Q_{10} and Q_{20}, respectively. The ultimate capacity for all tests was taken as the load producing a relative displacement of 20% of the helix diameter.

Table 1. Summary of Series-1 Triple-Plate Anchor Tests – Variable Spacing.

Helix Geometry	Relative Helix	Q_5 (lbs)	Q_{10} (lbs)	Q_{20} (lbs)

	Spacing (s/D)			
8	-	7487	10962	14450
8/8/8	0.75	8250	12500	16500
8/8/8	1.125	10500	15500	19000
8/8/8	1.5	12000	18000	22000
8/8/8	2.25	11000	22000	28000
8/8/8	3.0	12500	27000	39000
8/8/8	4.125	10500	28000	40000

Table 2. Summary of Series-2 Multi-Plate Anchor Tests – Constant Spacing.

Helix Geometry	Relative Helix Spacing (s/D)	Q_5 (lbs)	Q_{10} (lbs)	Q_{20} (lbs)
8	-	7487	10962	14450
8/8	1.5	6000	11000	17000
8/8/8	1.5	12000	18000	22000
8/8/8/8	1.5	15000	21000	24000
8/8	3.0	16000	22000	28000
8/8/8	3.0	12500	27000	39000

4.2 Efficiency of Multi-Helix Anchors

The results of the tests from Tables 1 and 2 may be described in terms of the Efficiency of the multi-helix anchors over a single anchor of the same diameter. The Efficiency of a multi-helix anchor may be defined as:

$$\eta = Q_{MU}/\Sigma Q_{IU} \times 100\% \qquad [1]$$

where:
η = Efficiency
Q_{MU} = Ultimate Uplift Capacity of Multi-Helix Anchor
Q_{IU} = Ultimate Uplift Capacity of Individual Single-Helix Anchor

The tests performed allow for the evaluation of the influence of plate spacing for a constant number of plates on Efficiency and for the evaluation of Efficiency of a multi-helix anchor of constant diameter as more plates are added with the same plate spacing. Calculated values of Efficiency from the measured loads at 5%, 10% and 20% relative displacements are given in Tables 3 and 4. Figure 2 shows the Efficiency of the multi-helix anchors in comparison to the capacity of a single-helix anchor as a function of relative helix spacing for Series-1 using the loads at 20% relative displacement. For a sufficiently large plate spacing that allows individual plates to fully develop capacity without interference from adjacent plates, the Efficiency should be equal to 100%.

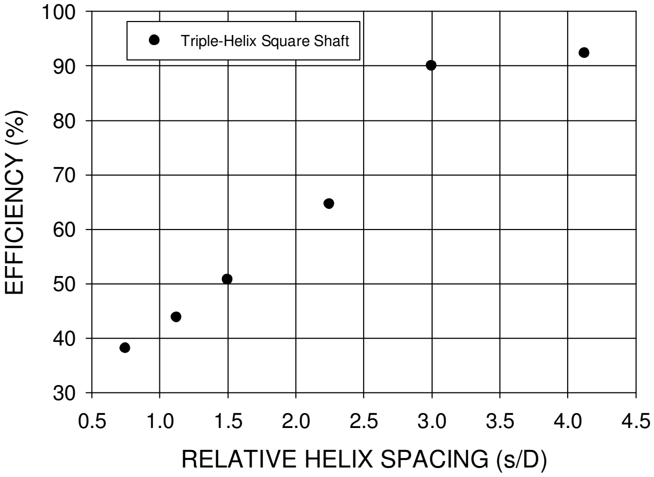
The results shown in Figure 2 suggest that the transition from Cylindrical Shear to Individual Plate occurs at a relative spacing of about 3, as previously assumed, but that the Efficiency does not equal 100% for plate spacing of 3 and beyond. This may suggest that there is some effect of installation on the full load development capability of multi-helix anchors, even with large plate spacing. Below a plate spacing of 3 the load capacity increases linearly, as would be expected from the Cylindrical Shear model as more area is added to the cylindrical prism of soil between plates.

Table 3. Summary of Efficiency of Series-1 Triple-Plate Anchor Tests – Variable Spacing.

Helix Geometry	Relative Helix Spacing	η_5 (%)	η_{10} (%)	η_{20} (%)
8	-	100	100	100
8/8/8	0.75	36.7	38.0	38.1
8/8/8	1.125	46.7	47.1	43.8
8/8/8	1.5	53.4	54.7	50.7
8/8/8	2.25	49.0	66.9	64.6
8/8/8	3.0	55.7	82.1	90.0
8/8/8	4.125	46.7	85.1	92.3

Table 4. Summary of Efficiency of Series-2 Multi-Plate Anchor Tests – Constant Spacing.

Helix Geometry	Relative Helix Spacing	η_5 (%)	η_{10} (%)	η_{20} (%)
8	-	100	100	100
8/8	1.5	40.1	50.1	58.8
8/8/8	1.5	53.4	54.7	50.7
8/8/8/8	1.5	50.0	47.9	41.5
8/8	3.0	106.8	100.3	96.8
8/8/8	3.0	55.6	82.1	90.0



No. of Helices	Helix Diameter (in.)	Relative Helix Spacing	Shaft Geometry	Q (lbs)	η	Reference
1	12	-	2 in. x 2 in. square	44000	-	Clemence et al. (1994)
2	12	3	2 in. x 2 in. square	60000	68%	
3	12	3	2 in. x 2 in. square	80000	61%	
1	16	-	7 in. round	139326	-	Sakr (2009)
2	16	3	7 in. round	188764	67%	

Figure 2. Efficiency of Cylindrical Triple-Helix Anchors in Sand as a Function of Relative Helix Spacing.

Figure 3 shows the calculated values of Efficiency for Series-2 anchor tests using multi-helix anchors with a constant plate spacing of both 1.5 and 3. These results suggest that the Efficiency decreases as more plates are added to the central shaft, for both relative plate spacings. Efficiency values are of course higher for a relative plate spacing of 3, as expected and as previously shown in Figure 2, and decrease at a much lower rate that for a relative late spacing of 1.5. These observations are again consistent with the transition from Cylindrical Shear behavior to Individual Plate behavior.

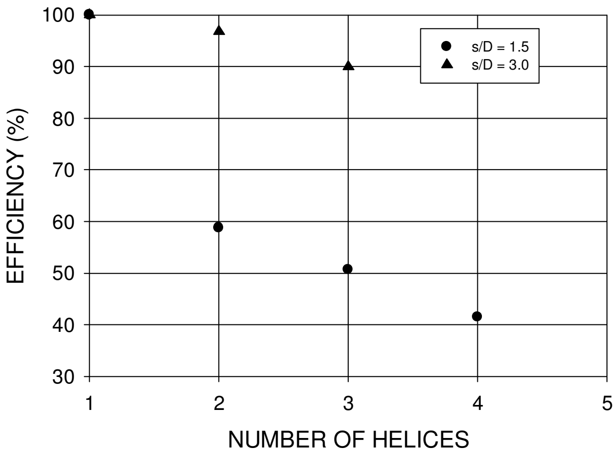


Figure 3. Efficiency of Cylindrical Multi-Helix Anchors in Sand as a Function of Number of Helical Plates at Constant Spacing.

The results shown in Figures 2 and 3 suggest that it may be possible to develop and alternative design procedure using an Efficiency approach based on the relative plate spacing to be used for a specific anchor.

4.3 Comparison with Previous Field Results

Table 5 gives a summary of previously reported ultimate uplift capacities for both single and multi-helix anchors in sand. In both of these cases, the calculated Efficiency for the multi-helix anchors is only about 66%, which is considerably lower than the values obtained in the current study and given in Table 4 for relative spacing of 3.0. Some of this difference may be related to the definition of ultimate capacity used by previous investigators. Clearly, additional field work is needed.

Table 5. Calculated Efficiency for Reported Multi-Helix Anchor Tests in Sand.

4.4 Comparison Between "Cylindrical" and "Tapered" Multi-Helix Anchors

In the current study, two "tapered" anchors with an average plate diameter equal to the diameter of the "cylindrical" anchors were tested to provide a comparison of the ultimate capacity developed between the two geometries. A comparison was made for relative helix spacings of 1.5 and 3.0. Results of the tests on "tapered" anchors are given in Table 6.

Table 6. Summary of Multi-Plate Anchor Tests on "Tapered" Anchors.

Helix Geometry	Relative Helix Spacing	Q_5 (lbs)	Q_{10} (lbs)	Q_{20} (lbs)
6/8/10	1.5	8000	14500	20000
6/8/10	3.0	15000	26000	30000

The results presented in Table 6 may be compared with results previously given in Table 1 and show that for this study the "cylindrical" anchors gave higher ultimate capacities in both cases; only about 10% higher for a spacing of 1.5 but about 30% higher for a spacing of 3.0. This may suggest that for sands, a "cylindrical" anchor may be preferred and may also suggest that there may not be a "taper effect" in uplift as previously suggested by Livneh and ElNaggar (2008). The lower capacities observed for the "tapered" anchors may also be related in some way to installation disturbance effects, which may not be present to the same degree in a "cylindrical" anchor. The 10 in. helix at the top of the "tapered" anchors may also contribute less proportional capacity. Clearly these issues are more complex than previously considered and as there is a lack of field data in this area additional tests in other sands would be useful to fully evaluate this behavior.

CONCLUSIONS

Results of a field investigation on the behavior of ultimate uplift multi-helix screw anchors in sand have been presented. The results indicate that:

1. The transition from Cylindrical Shear behavior to Individual Plate behavior of cylindrical multi-helix anchors with a fixed number of helical plates in sand occurs at a spacing of about 3.

2. However, even at a spacing of 3 and greater, the Efficiency is still less than 100%, suggesting that there may be installation effects to consider for helical anchors in sands.

3. The Efficiency of multi-helix anchors in sand decreases with the number of helical plates along the shaft. This decrease is more pronounced for closer plate spacing.

4. The use of anchor Efficiency may be an attractive alternative design approach for use with multi-helix anchors for any relative spacing or number of helices and should be investigated further.

The results presented in this paper were obtained from a single site. Although previously reported results appear to be consistent with the results presented in the current study, additional tests in other sands are needed to extend the present work.

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