

27 HELICAL ANCHORS AS WIND TOWER GUYED CABLE FOUNDATIONS

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SUMMARY: The current research is dedicated to developing design parameters and installation charts for the use of helical anchor foundation elements in application with 1 to 10 kW guyed and free standing turbines. The effects that dynamic loading and varying water table conditions have on the pullout capacity of helical anchors are the focus topics of this research. This study supports better predictions of helical anchors' capacities without intensive and intrusive soil tests. Field testing was performed on four helical anchors that were installed vertically to designated torque values to be tested for pullout capacity (tension). Static tests, short- and long-term, were performed on three anchors (one 4-helix and two 2-helix), and dynamic testing was conducted on one anchor (2-helix) in long-term testing followed by a static short-term pullout test. The conclusions observed from static and dynamic testing include the effects on an anchor's static uplift capacity from dynamic loading and influences from varying groundwater conditions, and the validation and further establishment of the torque correlation method. The findings in this paper indicate that cyclic loading influences on static uplift capacity are dependent on installation conditions, and that a rising groundwater table lowers the installation torque predicted uplift capacities.

Keywords: cables, cyclic loading, guyed cable foundations, helical anchors, wind turbine foundations.

INTRODUCTION

The proposed application of this study is to use helical anchors as a foundation system for small wind turbines (1–10 kW) guyed wires (tension applications). Helical anchors are currently used to anchor guyed wires of cell or transmission towers. However, the increased dynamic vibrations that a wind turbine adds to the tower and foundation system under working loads, as well as under extreme conditions (e.g., straight line winds, ice load or sudden furling shocks), require additional knowledge about the behavior of helical anchors under field conditions. These field conditions were simulated in this study by instrumenting a working tower to gather data on wind speed, direction and variability and tower response. These tower responses were then transmitted to the helical anchors in

an extensive testing program that included monitoring the soil-structure interaction of the helical anchor foundation under dynamic loads, subject to natural variations in both wind regimes, precipitation (water level) and varying helical anchor configurations. Through this study, uplift capacity of helical anchors subjected to long-term dynamic loads will be better understood.

The two most common methods used to predict the uplift capacity of multi-helix anchors are the cylindrical shear and the individual bearing methods (soil mechanics approaches). These two methods are time consuming to calculate, expensive and require detailed knowledge of soil properties prior, usually a combination of in situ testing (i.e. CPT, DMT, BST or etc) is needed to predict the uplift capacity. Also, with soil mechanics approaches the assumption is made that anchors are being installed into a homogenous layer. For uplift capacity in sand, the friction angle and uplift coefficient of lateral earth pressure are needed. However, for clay, the required parameters are undrained shear strength and adhesion^{1,2}. One of the purposes for this study is to find a fast, easy and reliable method for predicting the capacity of helical anchors, avoiding intensive soil testing seen in most soil mechanics approaches.

A less intensive empirical method that relates the installation torque to a predicted load capacity in both tension and compression could supply a “quick and clean” method to predict uplift capacity of helical anchors. Hoyt and Clemence³ analyzed 91 uplift load test at 24 different sites within varies soil types (i.e. sand, silt, and clay soils) in short term loading conditions. Their findings demonstrated that the consistency of the torque correlation modeling faired better when compared to the load capacity models of cylindrical shear and individual bearing, which may be due to the removal of several random variables that exhibit inconsistency in the cylindrical shear and individual bearing models. The proposed formula from Hoyt and Clemence relates the ultimate uplift capacity of the helical anchor to its installation torque:

$$Q_{ult} = K_t \times T \quad (1)$$

Where: Q_{ult} = Ultimate uplift capacity [lb (kN)], K_t = Empirical torque factor [ft^{-1} (m^{-1})], T = Average installation torque [lb-ft (kN-m)]

K_t values vary according to shape of anchor shaft, diameter of shafts, soil conditions, and other properties; a default K_t value of 33 m^{-1} (10 ft^{-1}) for most shaft conditions is recommended. Installation resistance does give insight into soil properties and the uplift capacity that the soil may yield with particular anchor geometry, but it does not incorporate the effects that dynamic loads (i.e. operational loads and wind loads) and fluctuating water tables will have on the capacity in the future. This study will observe the effects of dynamic loads and reductions in effective stress by rising water tables by monitoring groundwater depths and comparing static and dynamic testing in long- and short- term conditions.

BACKGROUND

Foundation systems designed for pullout or tensile loads are classified as anchors. These foundation types are usually used in applications to protect structures against overturning or pullout forces, but do have the capabilities of resisting compressive, lateral, and other loading combinations. Electrical transmission towers, retaining walls, offshore and

hydraulic structures, and many domestic structures are subjected to loads (e.g. earthquake, wind, lateral earth pressure, waves, and hydrostatic pressure) that generate strong tensile forces that overturn or pullout such structures. Previous work illustrates that the prediction of the uplift capacity of helical anchors considers the following factors: weight of anchor system, weight of soil mass bounded by the failure surface, friction and/or adhesion resistance along the failure surface, and suction developed under anchor plates. Anchors are created in a variety of configurations ranging from plate anchors, pile anchors, grouted anchors, pre-stressed concrete anchors, and single and multiple-screw helical anchors. Helical anchors are fabricated by welding single or multiple helical plates (helix) to a steel rod at predetermined spacing. Helical anchors are installed into the ground generally by applying torque to the shaft, causing the anchor to screw through the soil. An axial compression force is applied to make sure the anchor advances through the soil.

The main advantages of screw helical anchors compared to conventional concrete-cast anchors include: their relative ease for installation depending on soil conditions, mobility, cost-effectiveness, and the providing of overturning and uplift stability immediately after installation due to the elimination of the curing that is encountered in concrete anchors. Many factors are involved in predicting helical pullout capacities, ranging from site conditions (i.e. water table location, active zone location, frost level, and etc), anchor geometry, subsurface stratigraphy, and soil strength parameters (i.e. cohesion, friction angle, unit weights, etc).

Current design principles predicting uplift capacities rely on experience and empirical relationships that correlate installation torque to pullout capacity. Extensive use of helical anchors in foundation applications is prevented due to the lack of rational analytical techniques to describe anchor behavior accurately and consistently; a thorough understanding must be established before a suitable design method can be developed².

Predicting uplift behavior

The uplift behavior of helical anchors is dependent on many variables, and therefore modeling, which is generally based on bearing and frictional theories, is difficult. A consistent and general pattern of behavior has been correlated between helical anchors and other anchor types, in contrast with their differing geometry and installation procedures. Helical anchors behave in an intermediate case between grouted and spread anchors¹. A single helix anchor behavior is similar to a spread anchor, in which a cylindrical shear surface controls the behavior, with limited punching and cone breakout failures experienced when loose backfill is used over anchor excavations in stiff "host" soil. Multi-helix anchors form effective cylinders, or integral masses, when the helices are sufficiently close together. If helices are widely spaced, the anchor capacity behaves as a summation of each individual helical anchor³. Shallow and deep anchors have differing failure patterns; the most definite differences is shallow anchor's failure planes propagated to ground surface in a truncated cone, while a more isolated end-bearing failure is experienced in deep conditions. Figures 1 and 2 give basic illustrations of shallow and deep helical anchors.

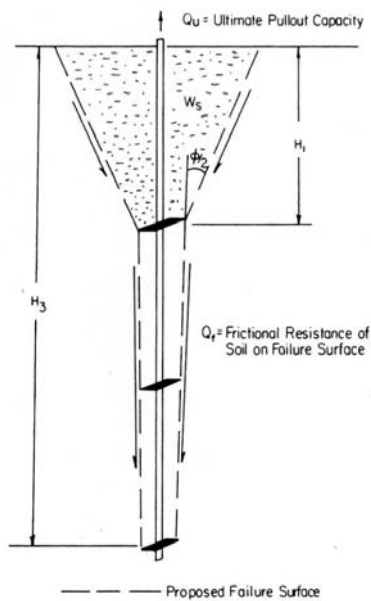


Fig. 1: Failure surface for shallow anchors¹.

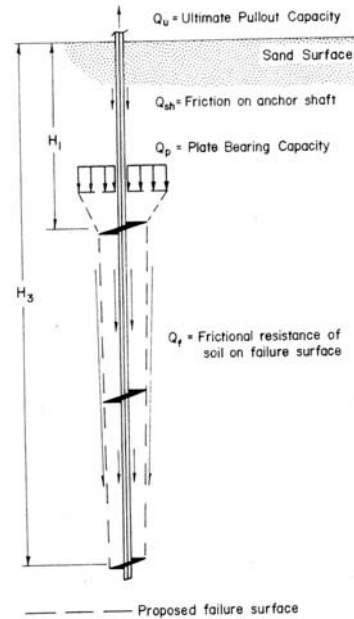


Fig 2: Failure surface for deep anchors¹.

Dynamic loading effects on uplift capacity

Research interest into dynamic capacity of helical anchors has increased over the past decade and half, due to some of the offshore applications that helical anchors are being used in. On the other hand, there are still very few studies that discuss the effects that helical anchors are subjected to from dynamic loads (i.e. ocean waves, wind loads, and etc). Previous research has shown that cyclic loading of anchors has a degrading effect on anchor behaviour; although repeated load applications (cyclical loading) tend to increase the post-static capacity of an anchor by stiffening the soil-anchor system. Total upward anchor movement is noticed to decrease⁴.

Clemence and Smithling⁴ performed a total of 14 tests on single helix model anchors (approximately 1/4 scale model of A.B. Chance SS Triple Helix) at H/D ratios of eight. Their results indicated that cyclic loading had deterring effect on anchor strength. The mechanism that triggered the ultimate failure in dynamic conditions was the reductions in horizontal stresses from the movement of sand grains from the edge of the helix to under the helix during repeated-cycled loading. In disagreement with other researchers, a significant reduction in the static capacity occurred after cyclic loading. The explanation given by Clemence and Smithling⁴ on the conflict between different researchers is the varying effects that installation has on in situ stresses in the soil. If installation loosens the soil, subsequent cyclic loading will compact the soil resulting in an increase in static capacity. An opposite effect may occur if anchor installation actually increases the density of foundation soil; cyclic loading will tend to loosen the soil and reduce static capacities.

TESTING SITE

The testing site was located directly east of the University of Oklahoma – Norman Campus Structural Engineering Lab, Fears. The site area was protected by a fence that enclosed approximately 5000 square feet of lightly vegetated topography. The topography

was relatively flat and dry. Anchors were installed about 4.6 m (15 ft) off center to avoid any coupling interaction during pullout. Figure 3 displays a basic layout of the site and the installation of anchors.

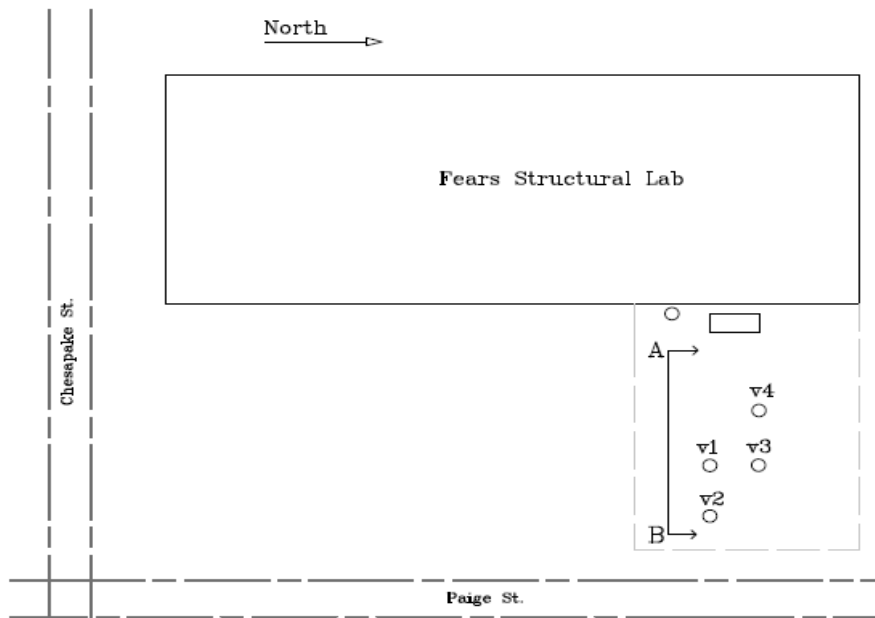


Fig. 3: Site layout of anchor installation.

The geology of the site was determined using several hand auger borings, existing soil maps, and previous explorations of the site. Table 1 displays a summary of the soil properties that were discovered in the foundation soil.

Table 1: Subsurface soil properties.

Depth (m)	Layer #	PL	LL	PI	Activity	Specific Gravity	USCS Symbol	Group Name
0 - 1	1	20.0	49.0	29.0	0.9	2.7	CL	Lean clay with sand
1 - 2	2	17.0	33.3	16.3	0.7	2.7	CL	Sandy lean clay
2 - 5	3	NP	NP	NP	NP	2.7	SM	Poorly graded sand
5 - 6.5	4	20.0	26.0	6.0	0.4	2.7	CL-ML	Silty clay with sand
6.5 - 7.5	5	NP	NP	NP	NP	-	-	Weathered shale

As displayed in Figure 3, four field anchors were installed at the testing site. Figure 4 gives an in-plane illustration of the foundation soil cross section with helical anchor locations. The bottom line across the cross section [at depth 4.5 m (14.7 ft)] indicates the lowest water table reading on March 16, 2007 during the 1st installation. The middle line gives the average depth of the water table, approximately 2 m (7 feet), from March 16, 2007 – January 9, 2008. The top line [at depth 0.6 m (2 ft)] shows the extreme rise, or most shallow depth, of the water table experienced during testing on July 16, 2007.

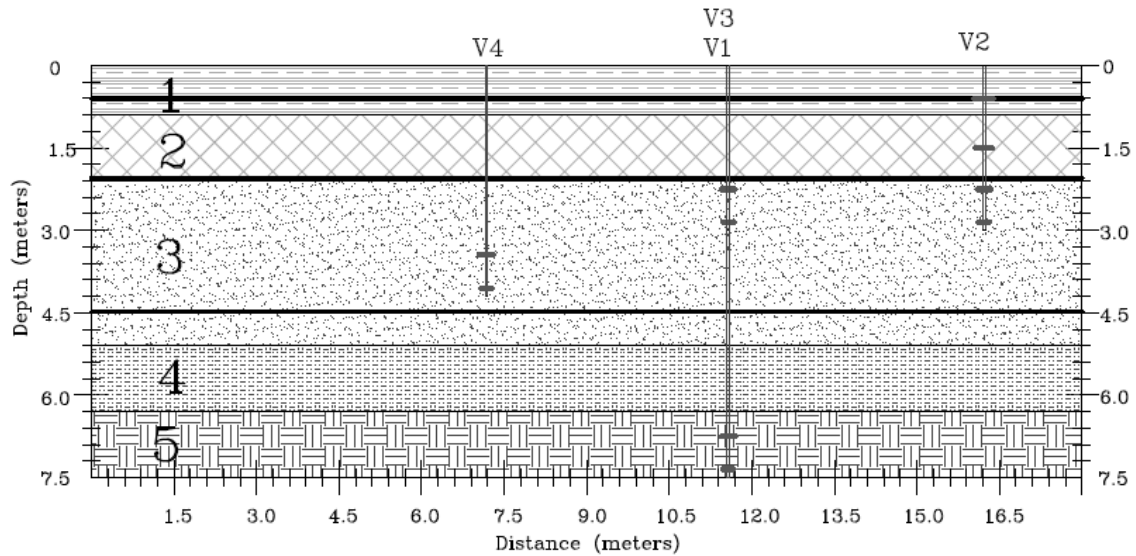


Fig. 4: Foundation soil cross section with installed anchors.

METHODOLOGY

Each anchor was screwed into the earth with a high-torque hydraulic drive which was mounted on a rotary auger drill rig. Each anchor was installed to depth that met the two-part criteria: (1) the top helix had to be at least $5D$ (D = diameter of top helix) into subsurface and/or (2) it must meet or exceed the designated torque value for three consecutive 0.3 m (1 ft) installation depth advances. Table 1 describes the installation conditions of the four field anchors. The average final torque signifies the mean value of the last three torque measurements; each advance was split into 0.3 m intervals until it met the chosen criteria.

Table 2: Anchor installation information.

Anchor Symbol	Description
V1	2 Helix, Avg. Final Torque = 5288 Nm (3900 ft-lb), Final Depth = 3 m (10 ft), Top helix @ 2.3 m (7.5 ft)
V2	4 Helix, Avg. Final Torque = 4610 Nm (3400 ft-lb), Final Depth = 3 m (10 ft), Top helix @ .8 m (2.5 ft)
V3	2 Helix, Avg. Final Torque = 3390 Nm (2500 ft-lb), Final Depth = 7.6 m (25 ft), Top helix @ 6.9 m (22.5 ft)
V4	2 Helix, Avg. Final Torque = 5017 Nm (3700 ft-lb), Final Depth = 4.3 m (14 ft), Top helix @ 3.5 m (11.5 ft)

Anchors V1 followed both criteria 1 and 2, while V2 (both installed on March 16, 2007), followed only criteria 1. Both were installed to 3 m (10 ft) and both torque averages exceeded the target torque of 4339 Nm (3200 ft-lb). The noticeable differences between the anchors are the number of helix plates and the H/D (embedment ratio) values. V1 is classified as a deep foundation ($H/D > 4$) in which $H/D = 9$ and V2 as a shallow foundation ($H/D < 4$) with an embedment ratio of 2. The similarities between the two anchors are the

torque values, which are similar. Observations were made that greater torque values were measured when advancing anchors with less helix plates, even though more plates provided higher friction areas. One reason for this observation could be the testing site soil variability. Performance comparison between V1 and V2 can be drawn from the uplift performance of different helical anchor geometries, the 5D requirement of top helix embedment and vary groundwater conditions from installation to testing.

Anchors V3 and V4 (installed on August 8, 2007) followed both criteria 1 and 2. The similarities between the two anchors are the number of helices and the deep foundation classification. V3 and V4 have H/D values of, 34 and 17. Limitations were met in the field with anchor V3; due to a weak pocket in the subsurface, the anchor could not meet the target torque of 4339 Nm (3200 ft-lb). Even after advancing the anchor 7.6 m (25 ft), the anchor only reached torques of 3390 Nm (2500 ft-lb) which is still sufficient for this study (Guyed Cable Design Load = 22,000 lb, and target anchor installation torque is calculated using a K_t factor of 33 m^{-1} [10 ft^{-1}] (Eq. #1)). Performance comparison between V1, V3, and V4 (post-static tested) can be drawn from the effects of dynamic loading on static uplift capacity and varying groundwater conditions from installation to testing periods. The torque correlation method is used as the bench mark for each static ultimate uplift capacity and its validity will also be compared with the actual ultimate capacity.

Figure 5 gives a description of anchor plate spacing and plate diameters. The helical plates spacing and diameters decrease from top to bottom and the pitch remains constant at each plate.

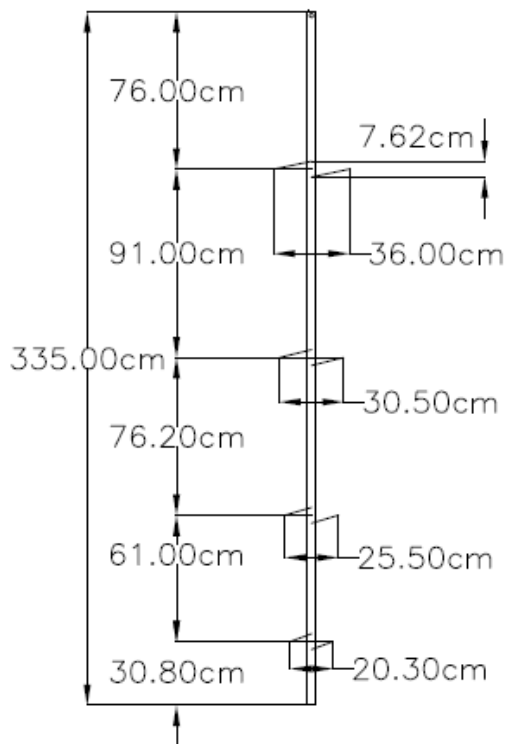


Fig. 5: Helical anchor geometry.

The helical anchors had a 44 mm (1.75 in) square shaft. The torque rating for this particular series of helical anchors is 14,900 Nm (11,000 ft-lb) and the ultimate uplift

capacity limit is 489 kN (110 kip). All tests used to determine the capacity of the anchors under tension load were completed with similar setups. The setup included a variable layer of cribbing depending on the shaft height above the ground surface, which changed on a test to test basis. The cribbing consisted of layers of railroad ties stacked perpendicular at each layer. Two 5.5 m (18 ft) long W beams (reaction beams) stretched across the anchor shaft resting on the cribbing at each end, with the shaft bisecting the reaction beams. A hydraulic jack/actuator was mounted above the reaction beam to test the anchors in tension. In static conditions, the instrumentation used to monitor the displacement of the cribbing and the anchors were dial gauges; in dynamic testing, potentiometers/wire pots were the instruments used to measure the dynamic displacements. All instruments were mounted on a reference beam that was installed perpendicular to the reaction beams and was not in contact with the foundation ground within a 3 ft radius. Figure 6 displays a basic setup for a static test.

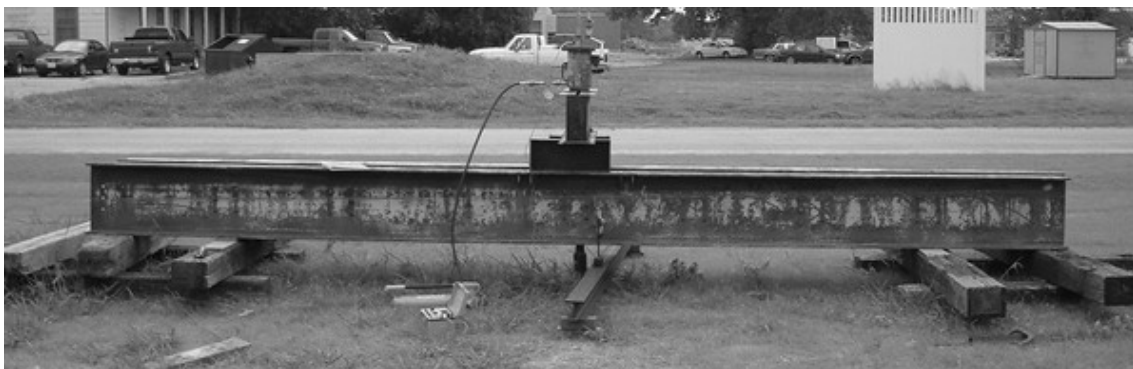


Fig. 6: Testing setup.

Seating loads were applied to the anchor that ranged between 10–20% of its predicted ultimate capacity in dynamic and static testing. Once the cribbing and anchor displacement was sustained at an equilibrium bearing pressure (minimal settlement), testing loads were applied. Static testing was completed in short term and long term periods. Loading was applied at 15% increments of the predicted ultimate uplift capacity and sustained on the anchor for 10–15 minutes (short term testing) and 1–24 hours (long term testing) or until displacement was minimal; intervals between load increments decreased drastically when failure was being approached. Increments were added until the anchor failed by either displacing 10% of largest helix plate (5 cm or 2 in), or the point at which there was continuous anchor movement at constant or decreasing loading¹. A 5 cm displacement is considered a failure in practice as mention by manufacture⁵. All data from static testing was recorded manually.

Seating loads in dynamic conditions were applied in the same portion as static testing. All dynamic loadings were applied in a sustained-repeated loading condition⁴. Testing procedures followed the sustained-repeated loading pattern, where the anchor remained in tension throughout the entire testing period to simulate operating wind loads as experienced from a guyed wire anchor foundation. Previous research data estimated that guyed wires connected to wind towers were under constant tension of about 4448 N (1000 lb), with vibrations in the 3–5 hertz range depending on the wind intensity. Regular operating loads were sustained on the anchor that oscillated between 4448 N (1000 lb) – 35,584 N (8000 lb). Extreme wind-shock loadings were applied in 0.5–2 hr intervals that simulated extreme operating and weather conditions (i.e. hurricanes, tornadoes, and high

winds) with oscillating load patterns ranging from 4448 N (1000 lb) to 88,960 N (20,000 lb). The cyclic loading frequency for testing was approximately 3–5 hertz. Dynamic testing was long term and lasted between 2–4 weeks. All dynamic data was recorded by data acquisition software at 50 hertz.

DATA AND ANALYSIS

Throughout the installation and testing procedures, the water table and rainfall data were monitored to quantify the effects that a varying water table (i.e. rising water table) has on the uplift capacity of anchors in static and dynamic conditions. Figure 7 gives an illustration of the rainfall data (received from Oklahoma Mesonet) and the water table depth over the installation and testing periods of the anchors. The water table depth was taken from a previous installed well near the testing site.

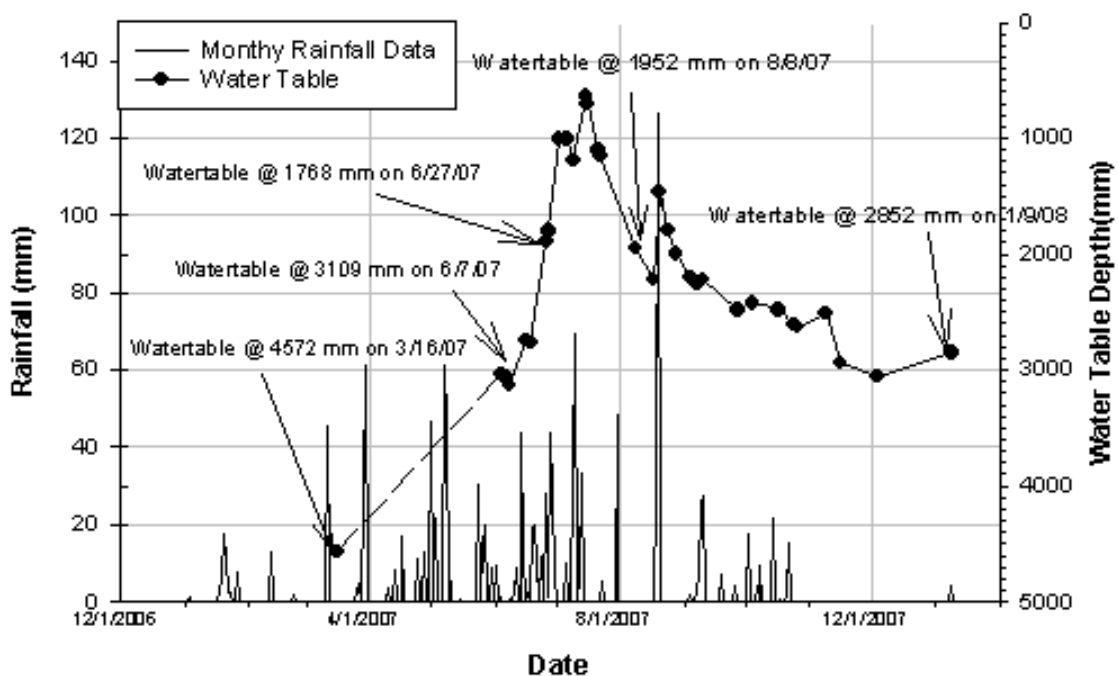


Fig. 7: Comparison plot of rainfall to water table depth.

The plot gives insight on how the water table is affected by rainfall, a major factor that contributes to groundwater fluctuations. Important dates are indicated as well, March 16, 2007 is when anchors V1 and V2 were installed. June 6 and June 27 are the dates in which V2 and V1 were statically tested, in that order. Anchors V3 and V4 were installed on August 8 and both were tested on January 9, 2008. V4 dynamic testing period began on November 30 and ended on December 19, 2007. Figure 8 displays a torque to depth relationship for each tested anchor.

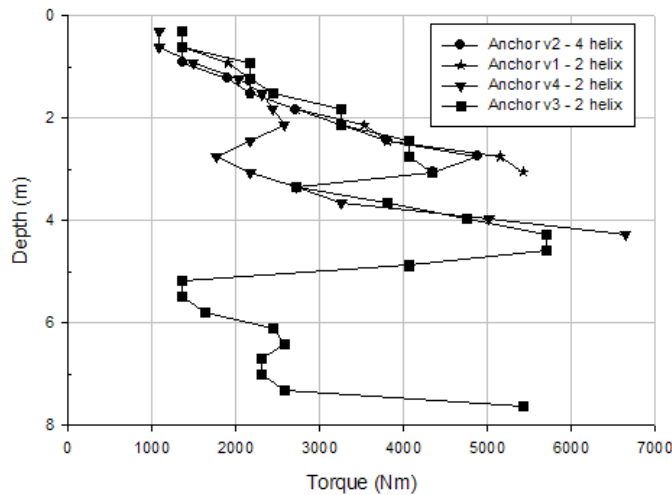


Fig. 8: Torque comparison plot for field anchors tested.

The data show that, generally, as installation depth increases, torque increases, unless a weak soil layer is encountered, as can be seen in anchor V3 around 5 m. The torque values for V3 then increased as the anchor entered the weathered shale. Significant amounts of anchor uplift capacity rest on the soil strength that the top helix is installed under. Referring back to Figure 4, illustrates that V1 top helix was under the sandy lean clay, V2 top helix was under the sandy lean clay, V3 top helix was slightly under the weathered shale but uplift strength may depend on the silty clay with sand, and V4 top helix was under the poorly graded sand. Obviously, predicted uplift capacities can be over-exaggerated when torques are affected by rock encounters and for this reason, average, not final torques should be used in torque-uplift correlation methods. Table 3 gives a summary of the anchors predicted and actual uplift capacities.

Table 3: Static uplift performances.

Anchor Symbol	# of Helix	Avg. Final Torque (kN-m)	Predicted Uplift Capacity (kN)	Field Test Static Uplift Capacity (kN)
V1	2	5.3	175	55
V2	4	4.6	152	160
V3	2	3.4	112	173
V4	2	5.0	166	197

- (1) All predictions were made with Hoyt and Clemence formula
- (2) Default K_t factor of 33 m^{-1} for predictions
- (3) V4 was a post-static test
- (4) V2 was a long term static test

Figure 9 shows a comparison plot of anchors V1 and V2 static uplift performances. The major observation notice in this plot is the significant drop in static uplift resistance experience by V1. The torque correlation method predicted that the anchor would have an uplift capacity of 175 kN, however, the anchor experienced failure at 55 kN under field static testing. The anchor installation torque measurements gave no indications of why the anchor would under-perform; the only variable from installation to testing was the groundwater table. The groundwater rose about 2.8 m from installation to testing anchor

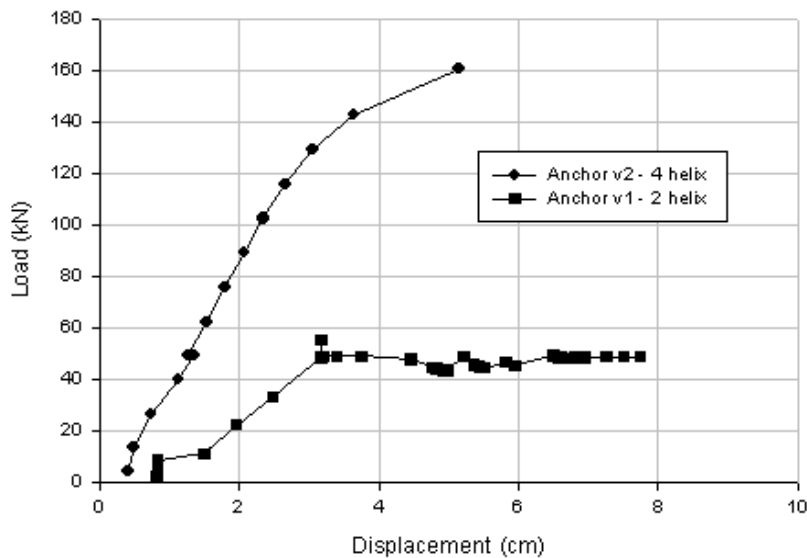


Fig. 9: Comparison plot of V1 and V2 anchors in static uplift.

V1 (March 16 to June 27, 2007). The water table at installation was approximately 1.5 m below the bottom helix, and then rose to approximately 1.0 m above the top helix. This water table rise changed the soil properties from unsaturated to saturated conditions, and therefore, decreased the matric suction and effective stress. Anchor V2, the only shallow anchor, did not meet the 5D requirement but its performance compares well to the torque correlation even with a 1.5 m rise in the water table from installation to testing. One reason that the uplift capacity was close to the prediction, despite the rising water table, is that the soil above the top helix remained unsaturated, therefore, the effective stress remained unchanged.

Figure 10 compares the uplift performance of V2, V3, and V4 anchors. V2, V3 and V4 all have different installation depths but can be compared on the basis of torque (within relative range of each other). All three anchors performed better than predicted, with anchors V3 and V4 displaying major increases in capacity, compared to the torque correlation method. A portion of this difference may be because the water table receded about 1 m between installation and testing, and the matric suction and effective stresses above the helices increased. Another reason for the difference, in V4 at least, was that V4 was first tested dynamically for 16 days. As mentioned in the literature, cyclic loads can have a compacting or loosening affect depending on installation conditions⁴. In this particular test, the installation may have had a loosening affect and thereby the cyclic loads compacted surrounding soils which increased the static uplift capacity. The 4-helix anchor, V2, had the lowest uplift capacity of the three anchors and the field capacity was close to the predicted installation torque capacity.

Figure 11 displays a 5 second snapshot of the behaviour of anchor V4 under a seating cyclic loading, ranging from 5–9 kN (1100–2000 lb). Wind loads were simulated at 3 Hz, using an actuator and hydraulic accumulator. This figure shows both the original data sampling frequency of 50 Hz and the reduced data analysis frequency of 10 Hz. As can be seen, there is relatively little difference between the two, and therefore, the 10 Hz data can be used with confidence when constructing long-term load-displacement comparisons of helical anchors.

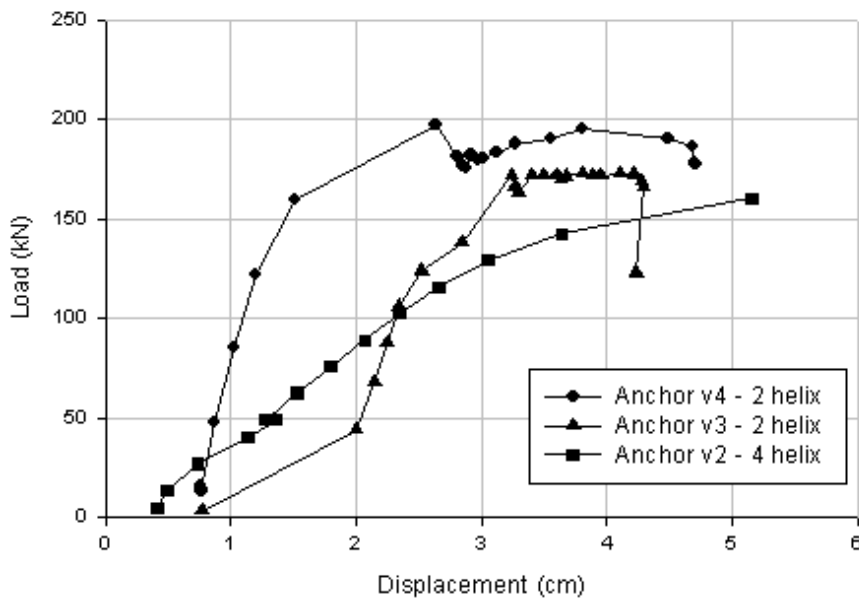


Fig. 10: Comparison plot of V4, V3, and V2.

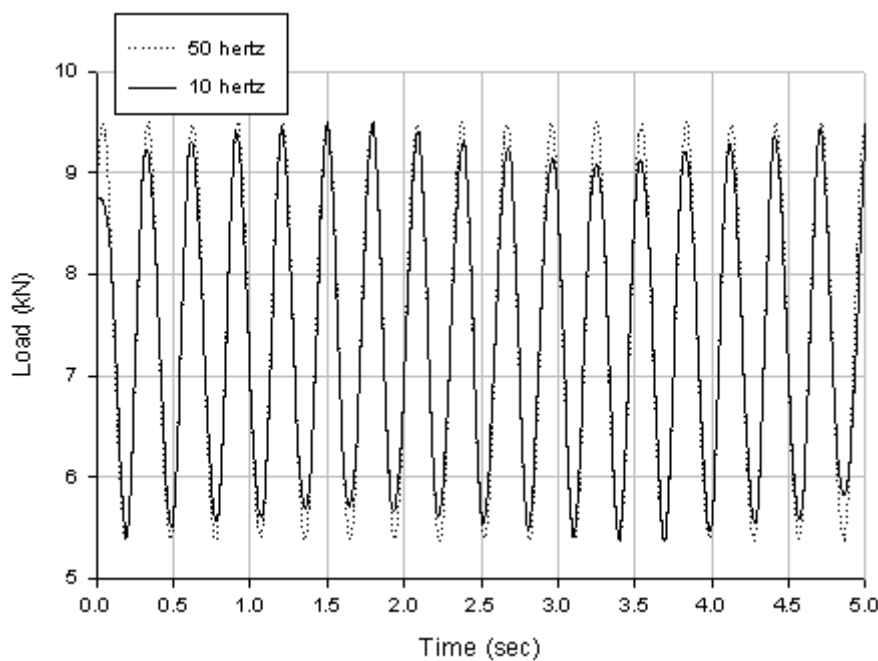


Fig. 11: 5 second snapshot of V4 loading behavior under dynamic loads.

Figure 12 displays a loading and displacement summary of V4 (2-Helix) over the testing period.

Figure 12 gives an hourly summary of the 16 day dynamic test on V4. The graph indicates initial displacement of about 2 cm after applying seating loads, and then another 3.75 cm as operating and extreme loading, 42–58 kN (9500–13,000 lb) was applied. The total displacement over the 16 day period was approximately 5.75 cm. After the dynamic testing was performed, a static test was performed and the ultimate capacity was found to be 197 kN, which was significantly higher than the torque installation predicted capacity of 166 kN.

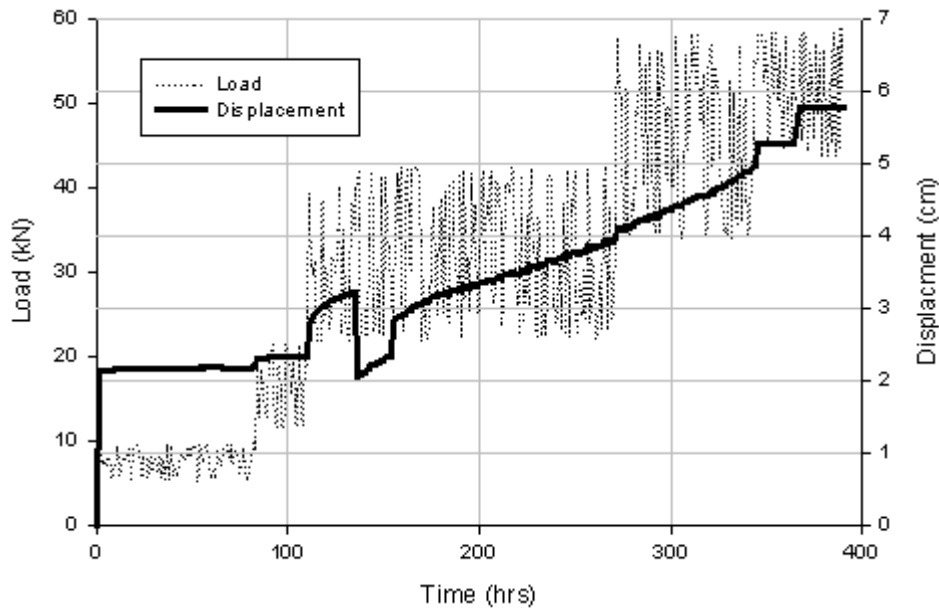


Fig. 12: Hourly summary of 16 day dynamic test on anchor V4 (2-Helix).

CONCLUSIONS

The key conclusions drawn from this investigation include:

1. Torque correlation designs must consider worst case groundwater conditions when designing helical anchor foundations systems,
2. A default K_t factor does not consider the changes that are encountered by soils between installation and testing (usage), or lifetime working conditions,
3. The torque correlation method under-predicted anchor uplift capacities, especially when the anchor was first subjected to dynamic loading, but over-predicted capacities when the water table rose,
4. Anchors with fewer helical plates are required to advance to deeper depths to achieve similar torque values as anchors with more plates, however, even with similar torques, the smaller anchors performed better in uplift, and
5. Long-term cyclic loading affects static uplift capacity.

Helical anchors can supply immediate support and cost effective alternative foundations for 1–10 kW wind turbines. This continued study will provide insight into the affects that take place when anchors encounter varying dynamic loads and fluctuating water tables. Knowledge of dynamic loading affects will greatly improve the prediction of helical anchor uplift behaviour. Torque-uplift capacity correlations must incorporate the reductions in effective stress and matric suction experienced during the span of an anchor's installation and operation. Better prediction factors that consider basic soil properties and subsurface changes (active zones, water tables, frost levels, etc) will greatly improve the predictions of helical anchor uplift behaviour.

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