The paper was published in the proceedings of XVI Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVI PCSMGE) and was edited by Dr. Norma Patricia López Acosta, Eduardo Martínez Hernández and Alejandra L. Espinosa Santiago. The conference was held in Cancun, Mexico, on November 17-20, 2019.

Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190131

Cyclic Stability of Helical Anchors Installed in a Sedimentary Sand Deposit

João P. da S. COSTA[a1] and Yuri D. J. COSTA[a]
[a] *Department of Civil Engineering, Federal University of Rio Grande do Norte, Natal, Brazil*

Abstract. Helical piles are steel foundation structures composed of one or more helical bearing plates soldered to a central shaft. They can be installed quickly and reused multiple times. The process causes minimal disturbance and loads can be applied immediately. Applications include foundations for residential and commercial buildings and anchoring for transmission towers and offshore structures. This research uses a criterion based on the accumulation of displacement to investigate how the stability of helical anchors is affected by the application of low frequency cyclic loadings. Multi-helix anchors were installed in a loose sedimentary sand. Two axial tensile load tests with cyclic loading were performed. Five loading steps were applied, each with 60 one-minute cycles and different mean loads and cyclic amplitudes. Moderate to fast displacement rates were observed during the cyclic steps. Increasing the mean load and the cyclic amplitude resulted in large accumulated displacements and higher rates of displacement accumulation. The loading parameters were plotted on a cyclic interaction diagram and classified according to their capacity to resist cycles in three groups: stable, meta-stable and unstable behavior. Steps with cyclic amplitude smaller than 10% of the static capacity exhibited stable responses and unstable behavior was observed for cyclic amplitude greater than 30% of the static capacity.

Keywords. Helical piles, foundations, anchors, cyclic loading, pull-out test.

1. Introduction

Helical piles can act as tensile members for retaining wall systems and utility guy anchors in projects of all sizes. The use of helical piles in Brazil initiated in the early 1990s and are currently used as anchoring for transmission towers, guyed masts and self-supporting towers [1]. These types of structures are subjected to wind loads. Designing for this type of cyclic action must include not only the static capacity of the anchors but also their displacement over time under load, also called creep.

Understanding of the cyclic behaviour of helical anchors on pure sand deposits, which are common on the coast of the Northeast of Brazil, is an area that needs improvement. To the best knowledge of the authors, there are no works in the available literature on the cyclic performance of full-sized anchors in these soils.

The main objective of this research is to study the effects of low frequency cyclic loads on the stability of deep multi-helix anchors installed in a deposit of loose sand, using a criterion based on the accumulation of displacements.

[1] Corresponding Author; E-mail: joaopaulodsc@gmail.com

2. Literature review

2.1. Cyclic events

Helical anchors are used to support many structures where the tensile loads fluctuate due to natural factors such as wind, wave, or tide action [2]. These loads can be called "cyclic" when they exhibit clearly repeated patterns and their amplitude and return period are regular [3]. Safe operation of structures under cyclic depends on their ability to resist cyclic loading [4]. Cyclic events can be defined by their number of cycles N, cycle period T, or frequency, f, mean load $Q_{mean} = (Q_{max}+Q_{min})/2$, and cyclic amplitude $Q_{cyclic} = (Q_{max}-Q_{min})/2$.

2.2. Effects of cyclic loads on anchor behavior

Capacity degradation of conventional piles subjected to cyclic loading has been observed in the field [5, 6] and replicated in laboratory [7]. DeJong *et al.* [8] attribute cyclic degradation in sands to a decrease in the normal stress due to cumulative contraction of the soil within the shear zone contacting the interface. However, increases in load capacity of helical anchors caused by stiffening of the soil-anchor system after cyclic loadings have been observed by Clemence & Smithling [9]. Victor & Cerato [10] suggest that the diverging results may be explained by how much the soil was disturbed during the installation process. The disturbance behavior of multi-helix anchors is affected by the relative density of sand. Tsuha *et al.* [11] suggest that in sands with low relative density, the penetration of the first helix causes total loosening of the particles and no additional loosening is caused by the passage of other helices. In contrast, the high degree of compactness of dense sands is reduced by the passage of the first helix but can be reduced further by the penetration of additional plates.

Poulos [5] associated cyclic axial failure of anchors under one-way loading with the accumulation of permanent displacements with increasing load cycles. Van Weele [12] attributed displacement accumulation to continuous rearrangement and possible crushing of particles.

Ghaly & Clemence [13] report that helical anchors under cyclic loads below 25 percent of the ultimate static resistance show almost no plastic upward creep. Based on this, Perko [14] recommends that service loads on helical anchors subjected to cyclical loading should be limited to 25 percent of the ultimate capacity.

2.3. Stability of foundations under cyclic loading

Tsuha *et al.* [4] defined cyclic failure as an accumulated displacement of 10% of the pile diameter, or when the displacement rate per cycle showed a sharp increase.

The main parameters that influence the number of load cycles a pile can sustain before failure are the mean cyclic load, the cyclic load amplitude, and the shaft and base resistances [1]. According to Puech *et al.* [15], cyclic response analyses of piles can be represented synthetically based on the combinations of mean load and cyclic amplitude using cyclic interaction (or stability) diagrams. The diagram can be divided in zones related to the accumulation of displacements caused by the cycles.

Tsuha *et al.* [4] proposed a quantitative definition of stability zones, associating them with the displacement accumulation rates. Three response classes were established for piles in tension applications: (1) A Stable (S) Zone, where axial permanent displacements stabilize or accumulate at rates below 1 mm per 10,000 cycles, with potential increases in shaft capacity. Failure in this case occurs after 1,000 cycles; (2) An Unstable (US) Zone, where displacements accumulate at rates above 1 mm per 100 cycles, with noticeable decreases in shaft capacity. Shaft failure occurs in less than 100 cycles; (3) An intermediate Meta-Stable (MS) zone, where displacements accumulate at moderate rates over tens of cycles without stabilizing. Failure occurs between 100 and 1,000 cycles.

According to Schiavon [1], the estimation of the number of cycles a foundation can sustain before failure is important to establish the interval between adjustments of the pre-stressing load in a guy-cable.

2.4. Degradation of strength elements due to cyclic loading

Schiavon [1] concluded that the behavior of helical anchors under cyclic loads is heavily influenced by helix bearing resistance, which functions as the pile base resistance of regular piles. The author noticed that shaft resistance at the end of cyclic loading was negligible. Instrumentation revealed that helical anchors resisted more than 92% of the maximum applied load in the last cycle. The author also concluded that shaft resistance is not fully mobilized in one-way tensile loading with low values of Q_{mean} and Q_{cyclic}. The shaft resistance is only fully mobilized, and exhibits degradation, in early cycles in loadings with higher cyclic amplitudes.

Urabe *et al.* [16] performed tension tests in single anchors and straight piles and observed that after shaft friction reached its ultimate value, at a displacement of about 30 mm, the anchor was the main element resisting the vertical load. In displacement-controlled axial load cycling Li *et al.* [17] observed that pile head capacity is reduced with increasing number of cycles, associated with a gap developed between the pile base and the sand underneath during cyclic unloading.

According to Andersen [18], cyclic loading may reduce the bearing capacity of a soil. Chow *et al.* [19] performed monotonic and cyclic load tests in plate anchors installed in dry dense sand. They observed that both types of testing have similar load-displacement behavior. However, cyclic loads with relatively low magnitude resulted in increases in the eventual ultimate capacity of the anchors, as a result of soil densification. This phenomenon was not observed with magnitudes approaching the monotonic capacity.

Cerato & Victor [20] found that cyclic loads applied at a frequency of 3-5 Hz may increase the ultimate capacity of anchors when the cyclic load/static capacity ratio is between 0.25 to 0.40.

Abdelghany & El Naggar [21] performed tests on helical anchors and observed that plain and grouted anchors exhibited reductions in the ultimate capacity between 5% to 10% after 15 load cycles.

Schiavon [1] carried out physical modelling in centrifuge on helical anchor models installed in dry sand. Cyclic loading did not affected helix bearing capacity even with large accumulated displacements after 1000 cycles, but shaft resistance degradation was observed during the first 100 cycles. In some cases, after 1000 cycles, post-cyclic degradation was observed even with the accumulated displacements below 10%D. The author also performed static load tests after the application of cyclic loading. Anchors with accumulated displacements greater than 10%D and up to 400 cycles were more likely to display increased post-cyclic capacity. Increases in post-cyclic uplift capacity were observed in the anchors previously subjected to a maintained Q_{mean} of around 50% of Q_T and a Q_{max} greater than 80%Q_T.

3. Site characterization

The experiments of this work were performed in a construction site within the main Campus of the Federal University of Rio Grande do Norte, in Natal, Brazil. The test site is located above a deposit composed of fine to medium uniform quartz sands. The results from a Standard Penetration Test survey conducted in the area show that the material at the depth where the plates were installed, between 2.5 and 4.0 meters, was a loose to very loose sand. The ground water table was not detected in the field survey.

4. Field tests

Static load tests were performed in the field to find the ultimate capacity of the helical anchors. Load tests with low frequency cycles (also called “quasi-static”, since the frequency is not sufficient to cause dynamic effects) were performed to evaluate the stability of the anchors. One helical anchor prototype was manufactured and used for both types of tests in a construction site.

The central shaft of the anchor was made with tubes with 73 mm in external diameter. The helical bearing plates were made with plates with 12.7 mm in thickness. The anchor consisted of one leading section with two helices with 250 and 300 mm in diameter attached to a section with a single 350 mm diameter helix. All plates were made with a pitch of 75 mm. Extension sections without plates were used to adjust the designated anchor length. Spigot and socket connections with bolts were used as couplings.

The anchor was installed into the ground until refusal using a drilling machine model MC150 unit, manufactured by CZM Foundation Equipment, Brazil. Its hydraulic motor has a maximum nominal torque of 9.3 kN-m.

A hollow hydraulic cylinder with 500 kN capacity, attached to a manual hydraulic pump, was used to apply the loads during the tests. The reaction system for the tests used two steel beams 3-m long, resting on timber logs with square section. The tension load applied on the anchor was measured using a hollow load cell installed above the hydraulic cylinder. Vertical displacements of the anchor head were measured with four dial gages, with a stroke of 50 mm and a resolution of 0.01 mm.

Four uplift static load tests were performed in the study area inside the construction site. Their execution was based on the Quick and on the Cyclic Loading tests described in ASTM D3689 – 07(2013)e1 [22]. A minimum distance of 5 times the diameter of the largest helix was kept between installations to prevent interference between tests.

Two uplift load tests with quasi-static loading were performed in the study area using the same apparatus used in the static tests.

Both tests were performed in five steps, each defined by a pair of cyclic loading parameters, mean load (Q_{mean}) and cyclic load amplitude (Q_{cyclic}), which increased after each step. In the first quasi-static load test, labelled Test 1, with Q_{min} increasing after each step. In the second quasi-static test, Test 2, Q_{min} was kept constant at 20 kN and the Q_{max} was increased after each step. The minimum load was applied to simulate the condition of anchors used to support guyed tower, which exhibit a fixed load at all times, even when not subjected to oscillating loads. Each step lasted one hour, during which 60 one-minute loading-unloading cycles were applied to the anchor. Within each minute, the applied load oscillated between the minimum and the maximum values.

5. Results and discussion

5.1. Quasi-static loading tests

Three out of four static tests were loaded until physical failure. The ultimate capacities from these tests are similar, and their average value, called static capacity, Q_T, is 193 kN.

The minimum and maximum loads applied during each step of Tests 1 and 2 and their corresponding loading parameters, cyclic and mean loads, normalized by the static capacity, are shown in Tables 1 and 2, respectively. In Test 1, both the pre-tensile, or minimum, load and the maximum load were increased after each step. In Test 2, only the maximum load was increased, while the minimum load values were kept almost constant.

Table 1. Cyclic loading parameters from Test 1.

Step	Q_{min} (kN)	Q_{max} (kN)	Q_{mean}/Q_T	Q_{cyclic}/Q_T
E-01	11.2	20	0.08	0.02
E-02	22.2	39.6	0.16	0.05
E-03	35.4	59.5	0.25	0.06
E-04	48.1	79.0	0.33	0.08
E-05	57.5	98.2	0.40	0.11

Table 2. Cyclic loading parameters from Test 2.

Step	Q_{min} (kN)	Q_{max} (kN)	Q_{mean}/Q_T	Q_{cyclic}/Q_T
G-01	18.2	39.9	0.15	0.06
G-02	18.7	59.8	0.20	0.11
G-03	17.6	79.3	0.25	0.16
G-04	19.5	99.4	0.31	0.21
G-05	20.2	147.8	0.44	0.33

5.2. Accumulated displacements

Accumulated, or permanent, displacement U_{acc} is the difference between the displacement reading after a load cycle and the displacement reading before the first cycle was applied. The accumulated displacements from Test 1 are shown in Figure 1. In all steps from Test 1, displacements accumulated faster in the first 10 cycles. The first two cycles from E-01 exhibited particularly large displacements compared with other steps (U_{acc} = 5.42 mm). This may be caused by the loose condition of the soil around the helical plates caused by disturbance during the installation of the anchor. The first loading cycles densified the soil and increased its stiffness.

The results from the steps in Test 2 are presented in Figure 2. The displacements from step G-05 are predominant. This last step had the highest mean load associated with highest cyclic amplitude and exhibited failure before reaching 60 cycles. The largest permanent displacements observed in steps G-01 to G-04 occurred during the first cycles, but none of them is considered as excessive as those in E-01, probably due to the lower amount of disturbance caused by installation and the higher minimum load, two times that from E-01. Cyclic failure condition was observed in the 5th step of Test 2.

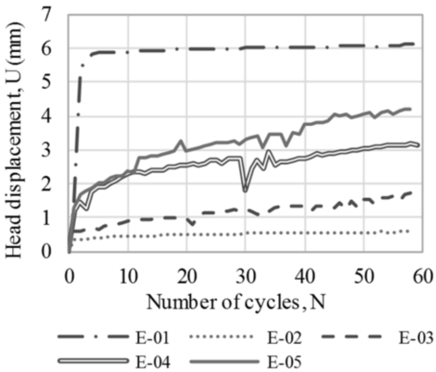

Figure 1. Accumulation of displacements: Test 1.

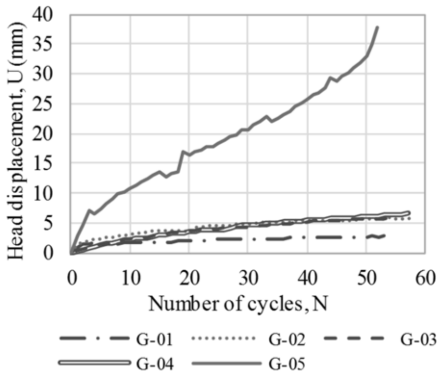

Figure 2. Accumulation of displacements: Test 2.

After large initial values, the displacements start to accumulate more slowly and at a constant rate. Displacement accumulation rate is the displacement increase after a load cycle. The mean displacement accumulation rates (U_{acc}/cycle) calculated from the last 50 cycles of Tests 1 and 2 are shown in Tables 3 and 4, respectively. The tables also show the number of cycles before failure, N_f, for the other steps estimated from the displacement recorded after the first 10 cycles and the rate of displacement accumulation from the last 50 cycles. The number of cycles was used to classify the stability of each step according to the criteria proposed by Tsuha *et al.* [4]. In steps classified as Stable, the displacement accumulation rates ranged from 4.40×10^{-3} to 23.3×10^{-3} mm/cycle. All Meta-Stable and Unstable tests exhibited high displacement rates, faster than 10.0×10^{-3} mm/cycle. An association of the displacement rate with the mean cyclic load reveals that displacements kept increasing at fast rates when the anchor was subjected to mean loads (Q_{mean}) higher than 20% Q_T and cyclic loads (Q_{cyclic}) higher than 6% Q_T (steps E-03 to E-05 and G-02 to G-05).

Table 3. Steps from Test 1 classified according to their stability.

Step	U_{acc}/cycle (mm/cycle)	N_f	Classification
E-01	4.40×10^{-3}	5,474	Stable
E-02	2.72×10^{-3}	10,845	Stable
E-03	16.5×10^{-3}	1,760	Stable
E-04	18.1×10^{-3}	1,534	Stable
E-05	39.1×10^{-3}	707	Meta-Stable

Table 4. Steps from Test 2 classified according to their stability.

Step	U_{acc}/cycle (mm/cycle)	N_f	Classification
G-01	23.3×10^{-3}	1,214	Stable
G-02	61.4×10^{-3}	438	Meta-Stable
G-03	80.5×10^{-3}	343	Meta-Stable
G-04	92.9×10^{-3}	298	Meta-Stable
G-05	644×10^{-3}	46	Unstable

5.3. Cyclic interaction diagram

Figure 3 shows all steps plotted against their cyclic loading parameters, cyclic and mean loads, normalized by the static capacity Q_T, in the form of an interaction diagram. The steps were classified into Stable (S), Meta-Stable (MS) or Unstable (U) zones using the quantitative definitions proposed by Tsuha *et al.* [4]. Steps with $0.02 < Q_{cyclic}/Q_T < 0.08$ and $0.08 < Q_{mean}/Q_T < 0.33$ exhibited moderate to high displacement rates but were expected to withstand more than 1,000 cycles before reaching the failure condition and are thus grouped within the Stable region of the chart.

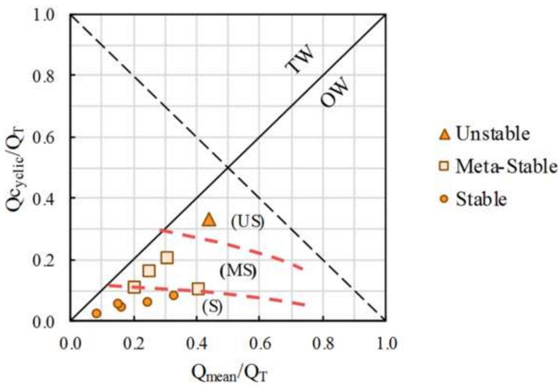

Figure 3. Axial cyclic interaction diagram: Tests 1 and 2.

The last step performed in Test 1, E-05, and steps G-02, G-03, and G-04 of Test 2, performed with $0.11 < Q_{cyclic}/Q_T < 0.21$ and $0.20 < Q_{mean}/Q_T < 0.40$, were expected to take between 298 to 707 cycles before failure and are grouped inside the intermediate Meta-Stable response zone.

In the last step of Test 2, G-05, Q_{cyclic}/Q_T is equal to 0.33 and Q_{mean}/Q_T is equal to 0.44. In this step, the anchor reached its failure condition, a head displacement of 30.0 mm, after 46 cycles and its cyclic response can be deemed Unstable.

The diagram also shows that the stability of a test is dependent on both cyclic loading parameters. For example, step E-03 is classified as Stable and sustains four times more cycles before failure than G-03, which is classified as Meta-Stable. Another example is the pair E-05 and G-02. The cyclic amplitude of both tests is close to 0.11 but the mean load acting on E-05 is twice that of G-05. Both are considered Meta-Stable but E-05 can sustain 61% more load cycles than G-02.

6. Conclusions

This research presents an evaluation of the behavior of helical anchors installed in a pure sand deposit. Two tensile load tests were performed with quasi-static loading cycles. Each test was comprised of five steps with different cyclic loading parameters. Moderate to fast displacement rates were observed during the cyclic steps. Increasing the mean load and the cyclic amplitude resulted in larger accumulated displacements and higher displacement accumulation rates. The number of cycles sustained before failure was estimated and the steps were classified according to their cyclic response: five tests were classified as Stable, four as Meta-Stable, and one exhibited cyclic failure and was classified as Unstable. Plotting the cyclic loading parameters of the steps normalized against the static capacity of the pile (Q_T) on a cyclic interaction diagram reveals the interaction effects of the cyclic loading parameters on anchor response, for steps with mean loads below 44% Q_T and cyclic amplitudes below 33% Q_T. The responses from steps with cyclic amplitude below 8% Q_T and mean load below 33% Q_T were considered Stable. The cyclic amplitudes of the steps with Meta-Stable response were higher than 11% Q_T and lower than 21% Q_T, with mean loads between 20% to 40% Q_T. One step reached failure before 100 cycles and was deemed Unstable. Its cyclic amplitude was 33% Q_T and its mean load was 44% Q_T.

References

[1] Schiavon J.A. (2016), *Comportamento de ancoragens helicoidais submetidas a carregamentos cíclicos*. PhD thesis, University of São Paulo and Nantes Angers and Le Mans University, São Carlos, Brazil.

[2] Hanna T., Sivapalan E. and Senturk A. (1978). "Behaviour of dead anchors subjected to repeated and alternating loads", *Ground Engineering*, 11(3): 28-34, 40.

[3] Andersen K.A., Puech A.A. and Jardine R.J. (2013). "Cyclic resistant geotechnical design and parameter selection for offshores engineering and other applications". In: *Proceedings of TC 209 Workshop 18th ICSMGE. Design for cyclic loading: piles and other foundations*, Paris, Presses des Ponts, ed. Puech A., 9-44.

[4] Tsuha C.H.C., Foray P., Jardine R., Yang Z., Silva M. and Rimoy S. (2012). "Behaviour of displacement piles in sand under cyclic axial loading", *Soils and Foundations*, 52(3): 393- 410.

[5] Poulos H. (1989) "Cyclic axial loading analysis of piles in sand", *Journal of Geotechnical Engineering*, 115(6): 839-852.

[6] Turner J. and Kulhawy F. (1990). "Drained uplift capacity of drilled shafts under repeated axial loading", *Journal of Geotechnical Engineering*, 116(3): 470-491.

[7] Fioravante V., "On the shaft friction modelling of non-displacement piles in sand", *Soils and Foundations*, 42(2): 23-33.

[8] DeJong J., Randolph M. and White D. (2003). "Interface load transfer degradation during cyclic loading: a microscale investigation", *Soils and foundations*, 43(4): 81-93.

[9] Clemence S. and Smithling A. (1984) "Dynamic Uplift Capacity of Helical Anchors in Sand". In: *4th Australia-New Zealand Conference on Geomechanics*, Perth, 88-93.

[10] Victor R. and Cerato A. (2008). "Helical Anchors as Wind Tower Guyed Cable Foundations". In: *Proceedings of the BGA International Conference on Foundations*, Dundee, Scotland: HIS BRE Press.

[11] 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*, 46(9): 1102-1114.

[12] Van Weele, A. (1979). "Pile bearing capacity under cyclic loading compared with that under static loading". *Proceedings of the 2nd International Conference on the Behaviour of Off- Shore Structures*, Bedford. 1: 475-488.

[13] Ghaly, A., and Clemence, S. (1998). "Pullout performance of inclined helical screw anchors in sand", *Journal of Geotechnical and Geoenvironmental Engineering*, 124(7): 617-627.

[14] Perko, H. (2009). *Helical piles: a practical guide to design and installation*. J. W. Sons, Ed.

[15] Puech, A., Benzaria, O., Thorel, L., Garnier, J., Foray, P., Silva, M., and Jardine, R. (2013). "Cyclic stability diagrams for piles in sands". In: *Proceedings of TC 209 Workshop 18th ICSMGE. Design for cyclic loading: piles and other foundations*, Paris, Presses des Ponts, ed. Puech A., 85-88.

[16] Urabe, K., Tokimatsu, K., Suzuki, H., and Asaka, Y. (2015). "Bearing capacity and pull-out resistance of wing piles during cyclic vertical loading", *Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering,* Christchurch, 9-17.

[17] Li, Z., Bolton, M., and Haigh, S. (2012). "Cyclic axial behavior of piles and pile groups in sand", *Canadian Geotechnical Journal*, 49(9): 1074-1087.

[18] Andersen, K. H. (2009). "Bearing capacity under cyclic loading — offshore, along the coast, and on land. The 21st Bjerrum Lecture presented in Oslo, 23 November 2007", *Canadian Geotechnical Journal*, 46: 513-535.

[19] Chow, S., O'Loughlin, C., Corti, R., Gaudin, C., and Diambra, A. (2015). "Drained cyclic capacity of plate anchors in dense sand: experimental and theoretical observations", *Géotechnique Letters*, 5(2): 80-85.

[20] Cerato, A. and Victor, R. (2009). "Effects of long-term dynamic loading and fluctuating water table on helical anchor performance for small wind tower foundations", *Journal of performance of constructed facilities*, 23(4): 251-261.

[21] Abdelghany, Y. and El Naggar, M. H. (2010). "Monotonic and Cyclic Behavior of Helical Screw Piles under Axial and Lateral Loading", *Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, 8.

[22] ASTM International (2013). *D3689M-07(2013)e1, Standard Test Methods for Deep Foundations Under Static Axial Tensile Load*, West Conshohocken, PA.