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High-Capacity Helical Piles for Stotrage Tanks-Case Study

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Abstract
Helical piles are widely used nowadays for variety of projects that span over a diverse range of industries which include electrical utility, oil and gas, commercial and residential, alternative energy such as solar and wind farms, and Municipal Infrastructure. Helical piles have several advantages over other conventional pile-types such as: can provide high compressive and uplift capacities at shallower embedment, quickest method of piling installation, suitability for construction in limited access areas, installation in different soil conditions, cost effectiveness and most importantly, helical pile installation is a vibration-free process. For storage tanks foundations application where operation loads are high and settlement is a concern, it is necessary to quantify the performance of the proposed pile design prior to construction commencement. This paper presents a full-scale axial compression load test executed on a high-capacity helical pile that is going to be used to support two sulphate storage tanks pads in an existing facility. The test setup and procedure are described. The results of the axial compressive pile load test and field monitoring of helical pile with quad helices installed in very stiff to hard clay shale soil are presented in this paper. A finite element model has been developed using Staad Pro software to study the load transfer mechanism. The data presented is therefore considered valuable to other researchers and engineers considering the use of helical piles to support high loads in urban areas. Based on the results of this study it was found that helical piles can develop a significant ultimate axial compressive resistance up to 3060 kN.

Keywords: helical piles, deep foundations, helices, full-scale load test, compression, high capacity

1. Introduction

Helical piles, also known as screw piles or screw anchors, are structural deep foundation elements used to resist axial compression, tension, and/or lateral loadings. Helical pile is an old type of deep foundation that was widely used in many countries before the advent of reinforced concrete piles (Kurian and Shah 2009). However, its application was limited to soft soil conditions since its installation was mainly dependent on human power. Its popularity has increased in recent years because of the rapid development of powerful hydraulic drive heads which shed more light on the advantages of helical piles compared to other conventional deep foundations systems. Helical piles can be easily installed very fast by relatively small/big equipment, can be removed and reused, no drill spoils and no requirement for concrete which means minimal environmental impact and they allow immediate loading upon installation completion. Likewise, in the case of high ground water level, helical piles save dewatering and/or pumping of the con-

truction site (Bobbitt and Clemence 1987).
Moreover, helical piles are economical alternative compared to traditional deep foundation techniques especially in resisting tensile loads and year-round weather installation, can be installed as single vertical pile or at an angle (battered) as well as they can be grouped to resisted very large loads. In addition, helical piles method of installation provides soil strength feedback and confirmation of soil stuffiness during installation for every pile location. In cases where encountering softer soils than anticipated, extensions can be applied to increase length to meet the required capacity.
Typical helical piles utilize one or more helical plates affixed around one end, the toe end, of a continuous central shaft of smaller diameter with a connection plate at the opposite or top end. Multiple helices can be attached to the central shaft and can be of equal diameters or have a smaller diameter towards the toe of the pile. Helical piles are basically rotated into the soil such that the helical plate engages with the soil to advance the pile into the ground. As a result, there is no vibration associated with the installation of helical piles, unlike most driven piles. Further, the helices are configured for soil displacement rather than soil excavation, so there is little or no spoil to be removed. Once the helical pile has been installed to the targeted depth, the helical plate(s) create a bearing surface to distribute the axial load to the underneath and surrounding soil.
Helical pile capacity is based on soil parameters and equations relating soil parameters, size of helix(s), shaft size and length, to capacity. Soil, however, is rarely homogenous and is highly variable so soil parameters used in design, along with capacity, must be validated in the field to ensure the foundation will perform as designed. Typically soil parameters are determined through geotechnical bore holes drilled at various locations and represent only a sample of what may be encountered due to the high variability. The capacity of deep foundations is typically validated through load tests and cannot validate 100% of the installed piles which still leaves a large margin for error in actual capacities vs. calculated capacities based on these two methods alone. Helical piles have a unique way to mitigate the error since it is industry practice measuring the energy, in the form of installation torque, required to advance the helical pile into the ground as a method to verify that soil parameters used in design are similar to what was used for the design at every pile location.

2. Case Study

Foundations for storage tanks are an important aspect of their design and construction. Common foundation types for storage tanks are reinforced concrete slab (slab-on-grad), ring foundation, or deep foundation consisting of big concrete slab supported by group of piles. Most importantly, the selected foundation type needs to be able to support the weight of the tank, its contents, and any additional loads that may be applied and transmit them safely to the underneath soil stratum fulfilling the serviceability and ultimate limit state design requirements. Factors affecting the selection of the foundation type: soil conditions, tank size and weight, site accessibility, space constraints and cost.
Two Sulphur storage tanks each 16.8 m in diameter have been proposed. Tanks will be spaced at 25.2 m center to center (i.e. clear spacing of 8.4 m (half a diameter) between tanks) and it was proposed to be founded on slab-on-grade. Each tank will weigh 5,900 metric tons when full of Sulphur including tank and accessories weight. Therefore, each tank will apply a total tank pressure of approximately 261 kPa at the foundation level. As can be seen in the subsequent section, using slab-on-grade as foundation for the proposed storage tanks is not feasible because of the expected excessive settlement. Therefore, a deep foundation option is selected which consists of a group of 56 helical piles capped with concrete pad to

support each tank. The main advantage of using helical piles for such application is the speed of installation and eventually pad construction, cost effectiveness, and their high resistance to compressive loads that can be achieved at shallower embedment compared to the other conventional piling. To exploit the viable advantages of helical piles in supporting big storage tanks, the results of the full-scale axial compressive pile load test on helical pile with quad helices installed in very stiff to hard clay shale soil are presented in this paper. In addition, the current paper summarizes geotechnical conditions, testing details, and presenting the field and numerical results. Finally, a finite element model was developed to study the load transfer mechanism between the pile shaft and helices on one end and the surrounding soil on the other end.

3. Subsurface Conditions

The testing site is located in Cheecham, approximately 70 kilometers (km) southeast of Fort McMurray, northern Alberta, Canada. Four test holes within the footprint of the proposed tanks to be used to describe the soil conditions. Subsurface soils in the proposed tank area generally consist of topsoil over variable composition of fill (silty clay, silt and sand) containing organics. Fill materials vary from soft to stiff and/or loose to compact condition. The fill extends to approximately 4m. Fill is underlain by stiff to hard clay shale of high plasticity.

Since the existing ground surface grade around the tank site varies, approximately 1.5 m depth of soil is required to be excavated to grade the existing ground to the design elevation. In addition, if shallow foundation (slab-on-grade) was to be used, existing fill material would need to be removed completely below the footprint of the tanks and replaced with granular fill (e.g. well-graded sand and gravel). It is expected that approximately 4 m thick granular fill would be placed below the tank slab-on-grade. Granular fill would be underlain by approximately 3 m thick layer of stiff clay shale followed by very stiff to hard clay shale. Therefore, it is important to assess the foundation serviceability by evaluating the order of settlement magnitude. The settlement estimation has been carried out considering site specific soil conditions encountered in the storage tanks area has been carried out. Classical Boussinesq chart was utilized to calculate stress distribution in the soil mass induced by tank loads. The effect of additional stress induced by adjacent tank load was also considered in the analysis. Tank pressure was applied on the foundation slab level. Soil weight unloading due to removal of 1.5 m thick existing soil was also considered in the analysis.

Table 1 summarizes the representative soil parameters used in the settlement estimation. The soil parameters are based on geotechnical investigation data, one-dimensional consolidation test results and empirical correlations from soil index test results in combination with local experience for similar soil conditions.

Estimated total settlement (consolidation and elastic) varies from 350 mm to 700 mm at the center of the tanks and 240 mm to 400 mm at the outside edge of the tanks. Estimated elastic settlement is approximately 30 mm and 15 mm at the center and edge of the tank, respectively.

Since the maximum tolerable total settlement of the tank foundation is 50 mm and differential settlement of 13 mm/10 m along tank circumference. Thus, estimated tank settlement is likely higher than the tolerable settlement if the tanks are founded on slab-on-grade. It is recommended that tanks should be founded on a deep foundation

Table 1: Soil Parameters used in Settlement Estimate

Soil Type	Compacted Granular Fill	Stiff Clay Shale	Very Stiff to Hard Clay Shale
Unit Weight, (kN/m3)	20	19	19
Initial void ratio, e_o	--	0.85	0.79
Over-Consolidation Ratio, OCR	--	2.0 – 3.0	1.5 – 2.0
Coefficient of Primary Compression, C_c	--	0.15 – 0.30	0.17 – 0.42
Coefficient of Primary Recompression, C_r	--	0.10 – 0.12	0.11 – 0.17
Elastic Modulus, E (MPa)	30	--	--
Layer Thickness, H (m)	4	3	18.2

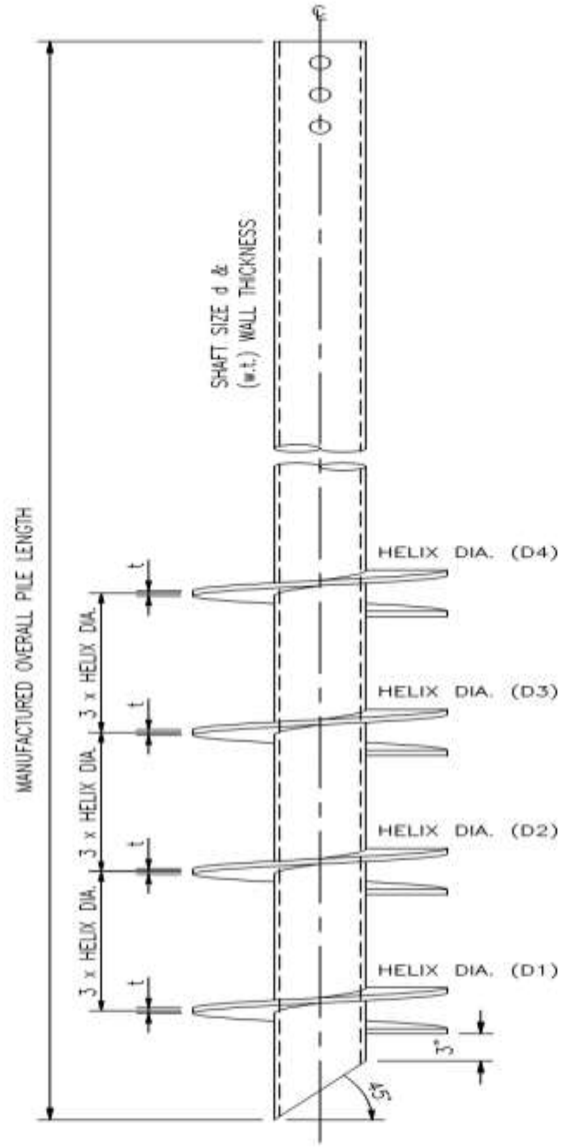
4. Test and Reaction Piles Geometrical Details

The tested pile was 406 mm outer diameter with wall thickness of 12.7 mm. It had four 762 mm diameter helices spaced at three times the helix diameter, 2.286 m. The overall length of the tested pile was 16.764 m. The pipe material was ASTM A252 Grade 3 steel. The helical plates were ASTM A36, grade 44W. The geometrical dimensions for the helical piles used to perform the pile load test are summarized in Table 2. Figure 1 provides a typical helical pile detail.

Table 2: Test and Reaction Helical Pile Geometrical Dimensions

Geometrical Properties	Test Pile (HP1)	Reaction Piles (HP2)	Main Beam Supporting Piles (HP3)
Shaft diameter (mm)	406.40	273.05	177.80
Shaft wall thickness (mm)	12.70	12.70	8.05
Helix diameter (mm)	762.00	762.00	660.40
Helix thickness (mm)	25.40	25.40	15.88
Number of helices	4	3	1
Total pile length (mm)	16,764.0	16,764.0	7,924.8
Installation torque (kN.m)	305.74	179.65	29.83

Figure 1: Typical helical pile detail



5. Pile Installation Load and Test Setup

Figure 2 shows a typical installation unit for a helical pile. Helical piles are installed through the use of mechanical torque applied at the pile head. The torque values were recorded at different depths and the final installation torque was taken as the average recoded values over the last six feet of installation which was 339 kN.m. The axial compression load test was carried out in accordance with ASTM standards D 1143-07. Since the main objective of the load test was to confirm the helical pile performance at the ultimate design load, Procedure A (Quick Test) was adopted wherein numerous small load increments were applied and maintained constant over short period of time intervals.

Figure 2: Typical helical pile installation unit

The load test setup consists of a total of seven piles including the test pile (HP1) and four reaction piles (HP2) and two main reaction beam holders (HP3). The reaction piles were installed to provide sufficient load reaction at a clear distance from the test pile of at least about 2.48 m and about 3.35 m from each other. HP3 helical piles were used to hold the main test beam in place before starting the test. Figure 3 shows the actual load test equipment setup using four reaction piles while Figure 4 shows the load test setup schematic details.

Caps made of a steel plate, pipe, and gussets were placed over the reaction piles and pins were placed horizontally through the cap and pile to attach the cap to the pile. The main reaction beam was placed temporarily on two HP3 pile type until the test started. Two secondary reaction beams were placed on four reactions piles (HP2). Four threaded bars and nuts were used to secure the reaction beam to the reaction piles. The connections were designed to adequately transfer the applied loads to the reaction piles and to prevent slippage, rupture or excessive elongation of the connections under the maximum load. A steel plate cap was welded to the top of the test pile to facilitate loading the pile. Two independent reference beams were set up parallel to the reaction beam near the test pile. A hydraulic cylinder was centered over the pile and a 1-inch-thick steel plate was placed on top. A load cell then was placed on the plates and another 1-inch-thick steel plate was placed on top of the load cell. A spherical bearing was placed on top of the load cell to maintain alignment of the applied load. Pile top movement was monitored using 2 dial indicators. The dial indicators have a precision of 0.001 inches. The pile was loaded by means of hydraulic jacks utilizing a hydraulic pressure gauge.

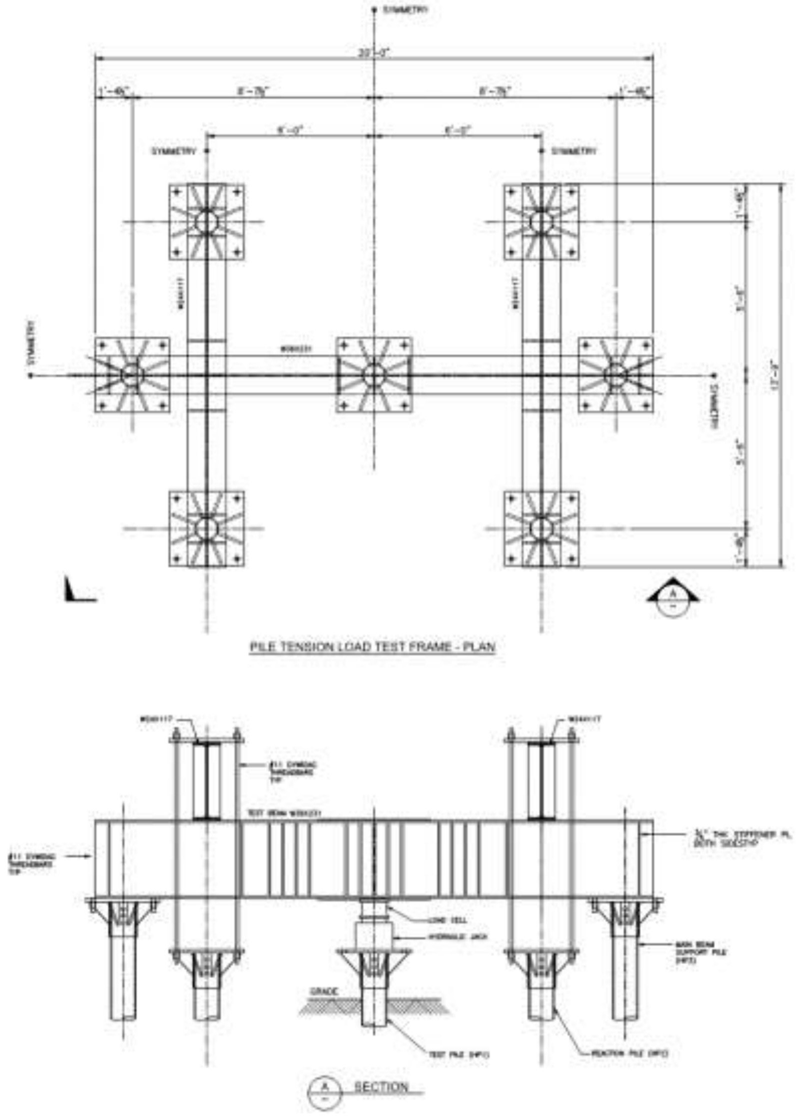
6. Load Test Procedure

The following load test procedure following Procedure A for Quick Tests for piles under axial compressive load were applied:

- Apply test load in increments equal to 5% of the anticipated maximum load and maintain the load constant for 4 minutes. Monitor movements using mechanical dial gauges at the end of each load increment.
- Add load increments until reaching maximum load (3060 kN). The test load was maintained for a longer period (about 10 minutes) to monitor creep behavior at two loading increments, 50% (1530 kN) and 100% (3060 kN) of the maximum load.
- Unload test pile in five increments and hold for 4 minutes with same monitoring intervals as for loading. When reaching zero load continue monitoring the readings for 10 minutes to assess the rebound behavior.

Figure 3: Actual Load Test Setup View

Figure 4: Load Test Setup Schematic Details

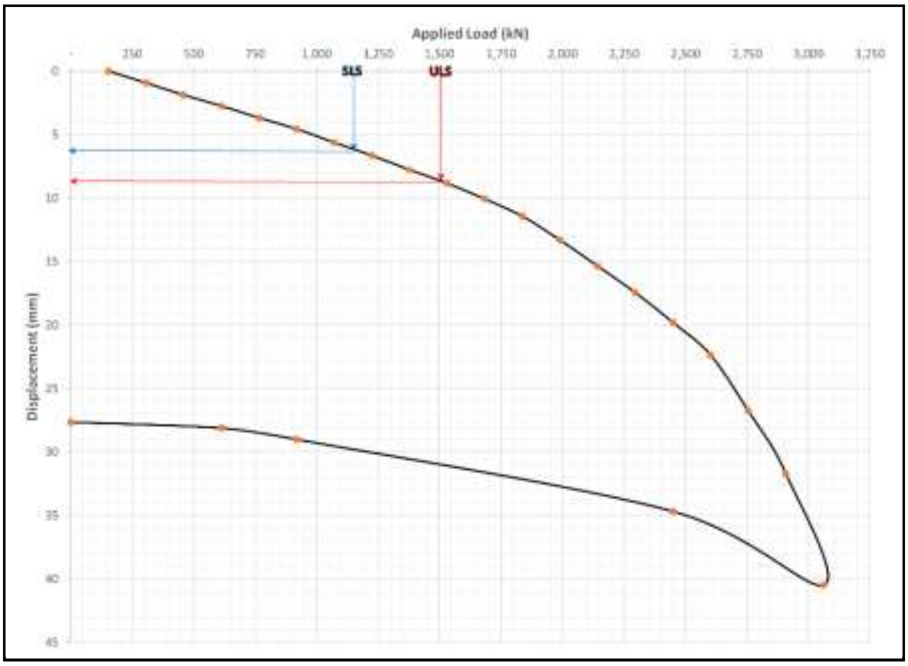


7. Pile Load Test Results and Discussion

The load displacement curve (Figure 5) is used to determine the allowable axial compressive pile capacity as well as to examine the pile performance in terms of settlement at the serviceability conditions. As was mentioned above, due to load test frame capacity, the aim of this test was not to fail the pile but to explore its behavior under the applied loads at both serviceability and ultimate limit state conditions. No plunging failure was observed during the application of the maximum applied load and was able to maintain the pressure throughout the whole interval which means tested pile hasn't reached a clear failure stage. Usually load displacement curve is characterized into three stages, linear, nonlinear and secondary nonlinear. In this test, the load displacement curve can be characterized only into two parts: the first linear part up to a displacement of about 11 mm, followed by a nonlinear component continued up to displacement of about 41 mm and the corresponding loads are 1830 kN and 3060 kN, respectively. However, the remaining permanent settlement due to soil compressibility is 27.5 mm.

As it can be seen on Figure 5, the pile moved about 8 mm at the ULS factored design load of 1530 kN while moved about 6 mm the SLS design load which was taken as 75% of the ULS factored design load, 1150 kN. It was required by the structural engineer for the storage tanks that helical piles to be designed for maximum settlement of 20 mm under the ULS factored design load. Therefore, the recoded settlement was way less than the allowed limit which means the proposed design is adequate for this application and will perform way better than anticipated. Moreover, according to the Canadian Foundation Engineering Manual 2006, the geotechnical resistance factor of 0.6 can be applied when full-scale static pile load is conducted. Therefore, considering the maximum applied load as the ultimate pile capacity, the proposed design can be rated to resist a design load of 1836 kN and the expected settlement is 12 mm.

Figure 5: Load Displacement Curve



8. Finite Element Model

A 3D finite element model was developed by utilizing the finite element package, Staad Pro, Figure 6 shows the model render view. The Linear Elastic Analysis procedure has been adopted in performing numerical modelling. The soil was modelled as linear springs with springs constants assigned to them for the global translational and rotational directions. Since this study involves only the axil vertical compressive load, only vertical transitional direction is considered. Therefore, constants were assigned to springs in the global vertical direction for all nodes on the pile shaft and helix plates. The pile shaft and the helix plate were modeled using plate elements that have the same thickness as the actual pile elements. A 3-noded (triangular) and 4-noded (quadrilateral) plate elements were utilized in the model. To ensure accurate model results, the maximum element aspect ratio was kept not greater than 4:1. The maximum load achieved on the load test was applied as a vertical load in the global direction and applied at the pile head.

The springs constant has been adjusted in the model to simulate the test pile behavior in the load test. The pile head moved 41.2 mm compared to 40.5 mm recorded in the field at applied load of 3060 kN. Hence, the developed numerical model results in good agreement with the load test results.

One of the pile design aspects is to check the structural strength of the pile material by ensuring that the stresses throughout the pile elements are less than the allowed limits. According to the results obtained from the numerical model, it was observed that the stresses throughout the pile elements were within the allowed limits with a maximum stress of 205 MPa observed on the pile shaft, Figure 7. Figure 8 shows the folding moment (bending moment) acting on the helix plate with maximum value of 1.09 kN.m/m'. Moreover, Figure 9 shows the shear stresses distribution in the helix plate with maximum value of 2.99 MPa.

Figure 6: Numerical Model Render View

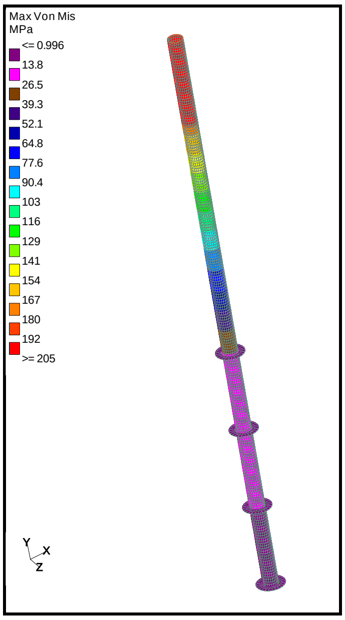


Figure 7: Stress Distribution in the Whole Pile

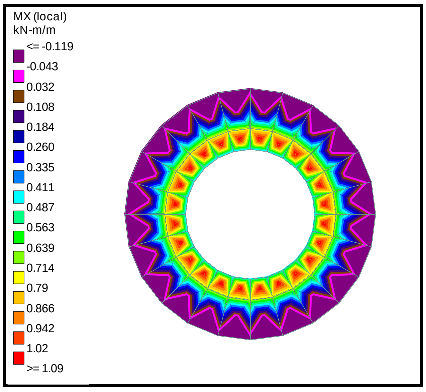


Figure 8: Folding Moment Distribution in the Helix Plate

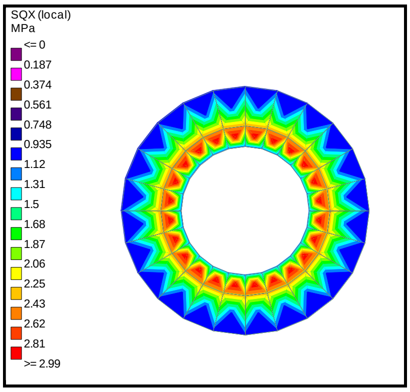


Figure 9: Shear Stress Distribution in the Helix Plate

9. Conclusions

The proposed helical pile design was successfully installed in very stiff to hard clay shale soil conditions and has achieved higher installation than expected. A full-scale pile load test was carried out to investigate the proposed helical pile design performance in supporting the storage tanks. Based on the load test results and the finite element model findings, the following conclusions may be drawn:

- The high compressive capacity of helical pile is likely to reduce the number of piles required to support the loads for the storage tanks which generally reduces the foundation costs. The speed of helical pile installation with minimal level of noise is really another differentiating factor for the use of helical piles to support such structures.
- Due to the capacity limit of the loading system, the tested pile hasn't been loaded to failure. This can be related to the fact that the achieved installation torque was higher than the expected value. However, the proposed helical pile design successfully surpassed the required axial compressive capacity of 1530 kN.. Therefore, helical piles can be used successfully to resist high compressive loads.
- The use of multiple helices is recommended to increase the pile overall axial capacity and keep the helix thickness within reasonable range.
- The results obtained from the numerical model follow the same trend of the load test results in terms of the vertical pile movement and they are in good agreement. Hence, the developed numerical model can be used to extrapolate the results and investigate the helical pile performance with different geometrical dimensions under the same soil conditions.

10. References

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