Torque correlation for solid steel square shaft helical piles

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ABSTRACT
Several analytical methods can be used to estimate the ultimate capacity of a helical pile. These methods involve calculations and the need for detailed information about the *in situ* soils. Alternatively, the most reliable method involves an empirical relationship between installation torque and ultimate capacity, and only requires soil types and blow counts (SPT N-values) to estimate installation depths. The results of several axial compression load tests in various soil types are examined to demonstrate that this empirical relationship can be conservative when estimating helical pile capacity in compression, and load testing can result in more efficient designs.

RÉSUMÉ
Les plusieurs méthodes analytiques peuvent être utilisé pour estimé la capacité des pieux d'acier vrillé. Ces méthodes nécessitent des calculs et de l'information détaillée du sol qui va supporter la charge. Pourtant, les plus exactes méthodes est resté celui impliquant une relation empirique entre l'installation toque et capacité ultimate, n'exigeant aucune information sur les sols plus que les types de sols et les valeurs SPT d'estimer profondeur. Les résults de plusieurs essais de charges compression axial dans divers types de sols sont examinés à montrer que cette relation empirique peut être conservateur dans l'estimation la capacité des pieux d'acier vrillé, et le charger les essais peuvent entraîner un dessin et modèles plus efficaces.

1 INTRODUCTION

The ultimate compression capacity of a helical pile has been estimated in the past using several methods. However, it has been generally agreed that many of the methods do not accurately predict the capacity of a helical pile in all situations.

Test results have proven that there is an empirical relationship between the ultimate capacity of a helical pile and the torque required to install it to a given depth. Using the correlation between installation torque and axial capacity, an empirical value, K_T, can be used to estimate the ultimate capacity of a helical pile (Hoyt & Clemence, 1989). In compression, this method can be considered conservative in many soil types where maximum torque can be achieved, i.e., when the soil is dense, and a grout column is created around the central shaft of the helical pile.

2 COMPRESSION LOAD TESTING OF HELICAL PILES

All load tests used in this study were carried out generally following ASTM standards for piles under static axial compressive load. The majority of the tests were completed following the Quick Load Test Method, although some were completed using modified test methods as specified by design engineers. In all instances, the piles were loaded in equal increments either to a maximum load, or to a point at which the pile could no longer maintain additional loading.

2.1 Testing apparatus set up

The compressive load tests were typically set up with a primary reaction beam supported by hardwood cribbing centred over the test pile. Two secondary reaction beams were used to hold down the primary beam and were located perpendicular to the primary beam at opposite ends. Each secondary beam was anchored with two reaction piles (one at each end) and fastened using a threaded rod adapter. A hydraulic load cylinder was centred on the test bracket and deflections were monitored using three dial indicators mounted on beams independent of the testing apparatus. Figure 1 illustrates a typical test set up from a top and a side view.

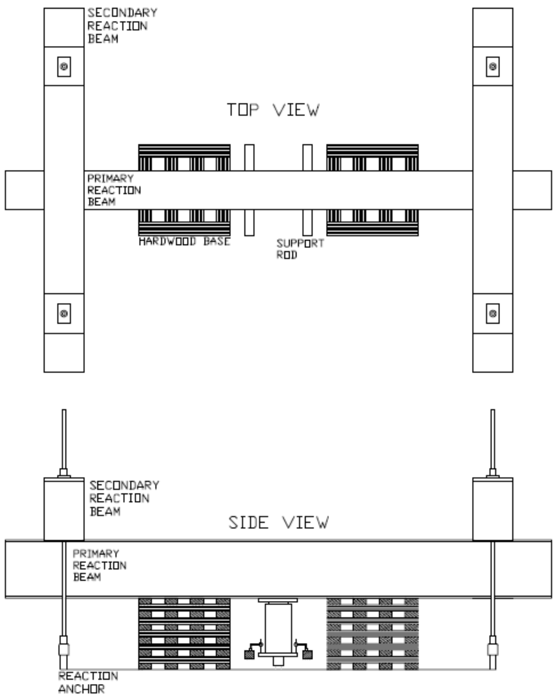

Figure 1. Typical compression test set up

In some instances, where the test loads were high or soil conditions were poor for tension loads, a pair of additional reaction piles was installed and another secondary reaction beam was used in the centre of the primary reaction beam.

3 LOAD TEST CASES

For the purpose of this study, 8 sets of load test data were used for establishing ultimate capacities. Two different sets were used for 1-½, 1-¾, 2, and 2-¼ inch (38, 44, 51 and 57 mm) solid steel, square shaft helical piles. Helical configurations, soil types, and depths varied in each situation. Each case will be referred to throughout the rest of the paper using the naming conventions as follows.

3.1 1-½ Inch (38 mm) square shaft helical pile load tests

1-½" (38 mm) Pile #1 was installed to a depth of 36 ft (11 m) in sand in Toronto, Ontario. The pile had a triple helical configuration with 8, 10, and 12-inch (200, 250 and 300 mm) helix diameters. It was tested to 120 kips (534 kN) with a maximum deflection of 1.589 inches (40 mm). 1-½" (38 mm) Pile #2 was installed to a depth of 15 ft (4.6 m) in sand in Ayr, Ontario. The pile had a triple helical configuration with 8, 10, and 12-inch (200, 250 and 300 mm) helix diameters. It was tested to 72 kips (320 kN) with a maximum deflection of 0.349 inches (8.86 mm). The installation torque of both piles was 5500 ft-lbs (7500 N-m), the maximum mechanical torque rating of the steel pile. The load test data of both are plotted in Figure 2.

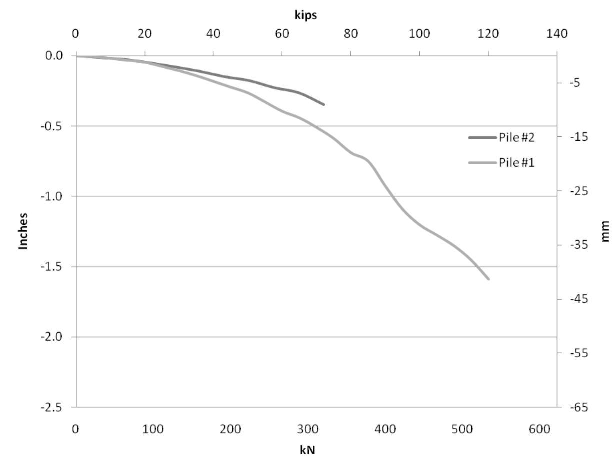

Figure 2. 1½" (38 mm)Piles #1 and 2 load test data

3.2 1-¾ Inch (44 mm) square shaft helical pile load tests

1-¾" (44 mm) Pile #1 was installed to a depth of 42 ft (12.8 m) in silty clay till in Toronto, Ontario. The pile had a triple helical configuration with 8, 10, and 12-inch (200, 250 and 300 mm) helix diameters. It was tested to 150 kips (670 kN) with a maximum deflection of 0.971 inches (25 mm). 1-¾" (44 mm) Pile #2 was installed to a depth of 36 ft (11.0 m) in clayey silt in Toronto, Ontario. The pile had a triple helical configuration with 8, 10, and 12-inch (200, 250 and 300 mm) helix diameters. It was tested to 180 kips (800 kN) with a maximum deflection of 0.867 inches (22 mm). The installation torque of both piles was 11 000 ft-lbs (14900 N-m). The load test data of both are plotted in Figure 3.

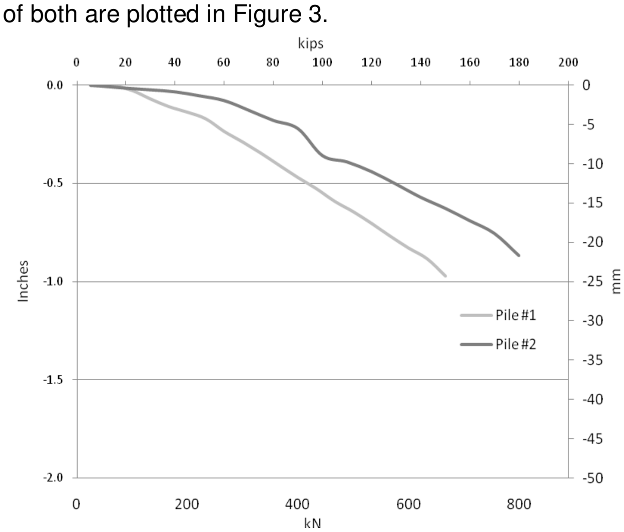

Figure 3. 1¾" (44 mm) Piles #1 and 2 load test data

3.3 2 Inch (51 mm) square shaft helical pile load tests

2" Pile #1 was installed to a depth of 72 ft (22.0 m) in silty clay in Windsor, Ontario. The pile had a quadruple helical configuration with 8, 10, 12, and 14-inch (200, 250, 300, and 350 mm) helix diameters. It was tested to

250 kips (1100 kN) with a maximum deflection of 1.711 inches (43 mm). 2" (51 mm) Pile #2 was installed to a depth of 28 ft (8.53 m) in sand and gravel in Cambridge, Ontario. The pile had a triple helical configuration with 8, 10, and 12-inch (200, 250 and 300 mm) helix diameters. It was tested to 288 kips (1280 kN) with a maximum deflection of 1.535 inches (29 mm). The installation torque of both piles was 16 000 ft-lbs (21700 N-m). The load test data of both are plotted in Figure 4.

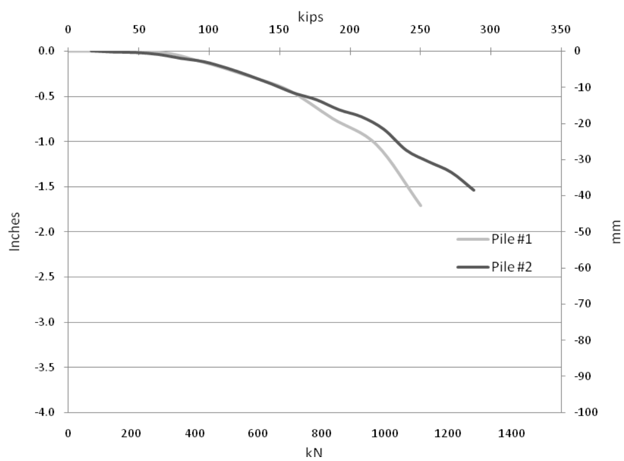

Figure 4. 2" (51 mm) Piles #1 and 2 load test data

3.4 2-¼ Inch (57 mm) square shaft helical pile load tests

2-¼" (57 mm) Pile #1 was installed to a depth of 19 ft (5.79 m) in sand and gravel in Woodstock, Ontario. The pile had a triple helical configuration with 6, 8, and 8-inch (152, 200, and 200 mm) helix diameters. It was tested to 250 kips (1100 kN) with a maximum deflection of 0.381 inches (10 mm). 2-¼" (57 mm) Pile #2 was installed to a depth of 36 ft (11.0 m) in sand in Whitby, Ontario. The pile had a triple helical configuration with 8, 10, and-12 inch (200, 250, and 300 mm) helix diameters. It was tested to 230 kips (1020 kN) with a maximum deflection of 0.630 inches (16 mm). The installation torque of both piles was 23 000 ft-lbs (31000 N-m). The load test data of both are plotted in Figure 5.

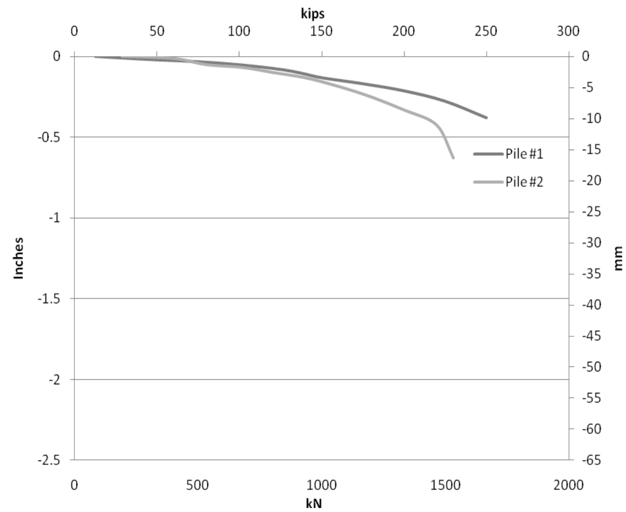

Figure 5. 2-¼" (57 mm) Piles #1 and 2 load test data

4 TORQUE CORRELATION

An empirical method using a torque coefficient, K_T, continues to be the most reliable method for determining ultimate capacity of a helical pile. The ultimate load of a pile is defined by Equation 1.

$$Q_{ult} = K_T \times T \qquad [1]$$

Where Q_{ult} is the theoretical ultimate capacity of the pile, and T is the installation torque. For the solid steel, square shaft helical piles used in this study, a K_T value of 10 ft^{-1} (33 m-1) was used. This value is the recommended and industry-accepted value for compression loads. This value is usually lower for round and hollow shaft piers. This relationship is developed on the justification that the torque is a function of the energy necessary to surmount the soil's shear strength.

4.1 Torque correlation and test data

Load test data from 64 tests from four different sizes of helical piles, in varying soil conditions, depths and helical configurations were used to investigate the relationship between pile capacities and K_T values. Figure 6 shows the load-deflection data of 1-½ inch (38 mm) square shaft helical piles compared to the rated capacity based on a K_T value of 10 ft^{-1} (33 m-1).

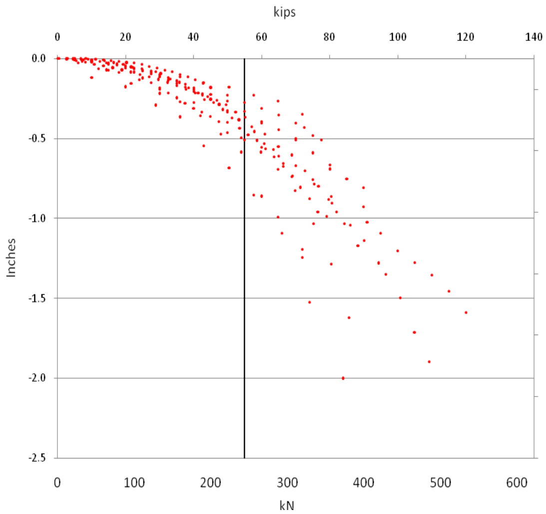

Figure 6. 1½ Inch (38 mm)Square shaft load test data

The vertical line indicates the rated ultimate capacity of 55 kips (245 kN). Note that none of the tests reached 1 inch (25 mm) deflection at their rated ultimate capacity. Figures 7 to 9 show the load-deflection data of 1-¾, 2, and 2-¼-inch (44, 51, and 57 mm) and square shaft helical piles compared to the respective rated capacity based on a K_T value of 10 ft^{-1} (33 m-1).

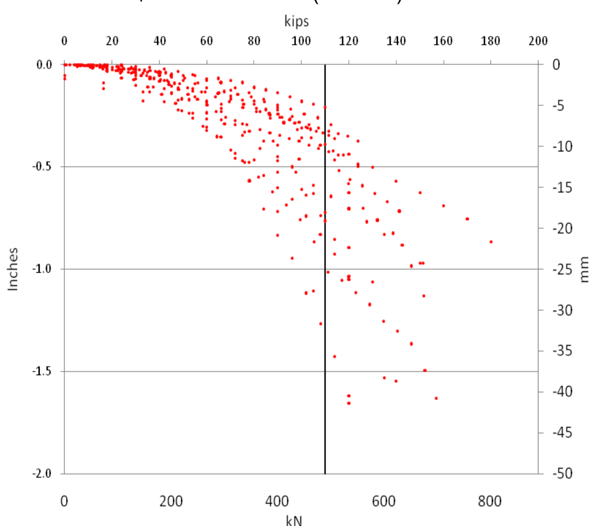

Figure 7. 1¾" (44 mm) Square shaft load test data

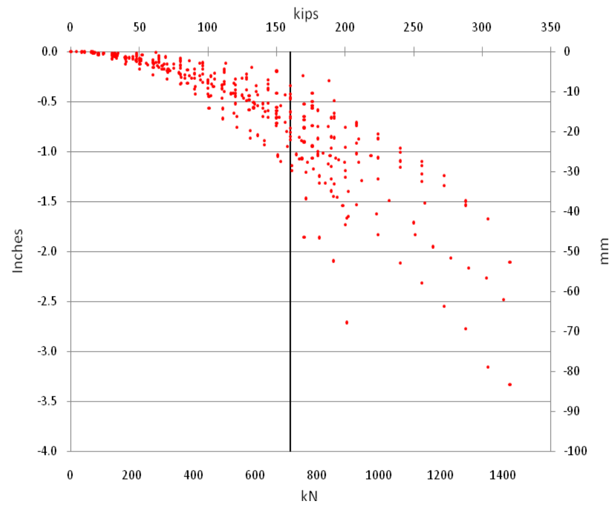

Figure 8. 2" (51 mm) Square shaft load test data

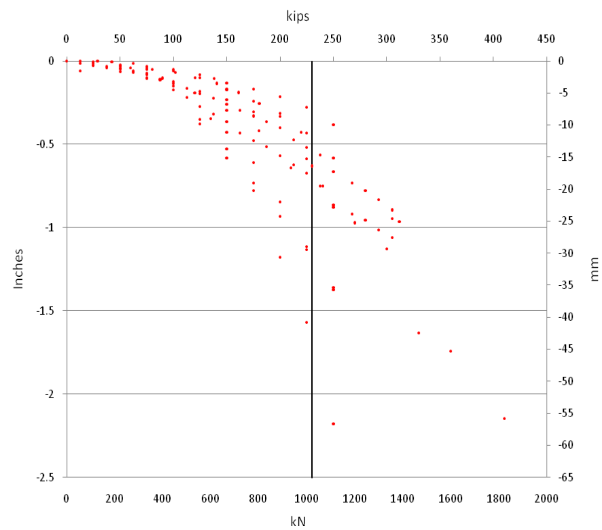

Figure 9. 2¼" (57 mm) Square shaft load test data

Figures 7 to 9 show that some deflections exceeded one inch (25 mm). However, the majority of the deflections were below one inch at the rated ultimate capacity.

5 ALTERNATIVE PILE CAPACITY METHODS

There are many different methods used to determine ultimate pile capacity. The usage of these methods depends on a variety of factors, such as pile type, engineer's preference, soil types, and location. Various methods were applied to load test data to investigate the effectiveness and reliability of these methods in determining ultimate capacity of helical piles.

5.1 Chin-Kondner's Method (Fellenius, 1990)

This method determines the limit load of the pile using the assumption that the load and deflection relationship is hyperbolic. The deflection values of a load test are divided by the respective load value, and the quotient is plotted against the load. Save for initial variations, the relationship is linear, and the reciprocal of the slope is the failure load. The Chin-Kondner's ultimate loads are summarized in Table 1 along with the rated capacity for a selection of helical piles.

Table 1. Chin-Kondner's ultimate loads

Pile ID	Rated Ultimate Load, kips (kN)	Chin-Kondner's Ultimate Load, kips (kN)
1½" Pile #1	55 (245)	152 (676)
1½" Pile #2	55 (245)	129 (574)
1¾" Pile #1	110 (490)	395 (1756)
1¾" Pile #2	110 (490)	403 (1793)
2" Pile #1	160 (710)	293 (1303)
2" Pile #2	160 (710)	385 (1712)
2¼" Pile #1	230 (1020)	386 (1717)
2¼" Pile #2	230 (1020)	266 (1183)

The Chin-Kondner loads are higher than the rated loads in every case. The difference ranged from 16 to 266 percent.

This method was very easy to compute and was done using a spreadsheet program. Its effectiveness is limited by the assumed hyperbolic load-deflection relationship, as typical test results sometimes followed a parabolic curve or other trends.

5.2 Manufacturer's Method

The manufacturer's recommended method defines ultimate load by determining a deflection value as a function of the pile, and the load at which that deflection occurs is the ultimate load. The deflection value is a product of the elastic deformation of the pile, plus either 8 percent of the largest helix diameter, or 10 percent of the average helix diameter. The intercept between that line and the load-deflection curve is the ultimate load for that pile. The ultimate loads determined by this method are summarized in Table 2 along with the rated capacity for a selection of helical piles.

Table 2. Manufacturer's method ultimate loads

Pile ID	Rated Ultimate Load, kips (kN)	Manufacturer's method Ultimate Load , kips (kN)
1½" Pile #1	55 (245)	118 (525)
1½" Pile #2	55 (245)	90 (400)
1¾" Pile #1	110 (490)	183 (814)
1¾" Pile #2	110 (490)	192 (854)
2" Pile #1	160 (710)	282 (1254)
2" Pile #2	160 (710)	300 (1334)
2¼" Pile #1	230 (1020)	280 (1246)
2¼" Pile #2	230 (1020)	245 (1090)

In each case the loads are higher than the rated loads. The difference ranged from 6 to 115 percent increase.

This method was also very easy to compute and a spreadsheet program was used to compute the capacities. Its effectiveness is limited by issues arising from determining the elastic deformation in a helical pile for multiple reasons. The elastic deformation is difficult to calculate when the pile is installed with a grout column because of variations in size and length of the grout. The elastic properties are also affected by the helices on the lead section of the pile; the helices will affect the deformation. However, it is very difficult to calculate or determine this effect. As well, in some instances the load-deflection curve did not intersect the allowable deflection line because the test was stopped prior to that point. In these cases the ultimate loads had to be extrapolated which means the ultimate loads are not necessarily applicable to the pile (extrapolation is not recommended).

5.3 Mazurkiewicz's method (Fellenius, 1990)

This method determines the limit load of the pile using the assumption that the load and deflection relationship is parabolic and determines the load graphically. The load-deflection curve is plotted and a series of evenly spaced lines are drawn perpendicular from the deflection axis to the curve. At the points where these lines meet the curve, lines are drawn perpendicular to the load axis. From the point where the lines meet the load axis, lines at 45 degree are drawn to intersect the line above. The points where these lines intersect approximately form a straight line; this line intersects the load axis at the Mazurkiewicz ultimate load. This method is demonstrated in Figure 10 for clarity.

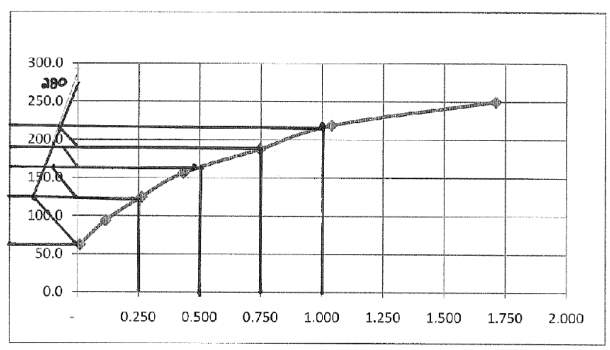

Figure 10. Illustration of Mazurkiewicz's method

The Mazurkiewicz ultimate loads are summarized in Table 3 along with the rated capacity for a selection of helical piles.

Table 3. Mazurkiewicz's ultimate loads

Pile ID	Rated Ultimate Load , kips (kN)	Mazurkiewicz's Ultimate Load , kips (kN)
1½" Pile #1	55 (245)	96 (427)
1½" Pile #2	55 (245)	100 (445)
1¾" Pile #1	110 (490)	250 (1112)

1¾" Pile #2	110 (490)	270 (1201)
2" Pile #1	160 (710)	290 (1290)
2" Pile #2	160 (710)	350 (1557)
2¼" Pile #1	230 (1020)	300 (1334)
2¼" Pile #2	230 (1020)	260 (1157)

The Mazurkiewicz loads are higher than the rated loads in every case. The difference ranged from 13 to 145 percent.

This method was computed by hand. Its effectiveness is limited by the assumed parabolic load-deflection relationship and typical test results sometimes did not reflect this. In all cases the deflection increased with the load, but the ratio increased at higher loads. This method was more effective when the ratio was higher. It is important to remember the degree of freedom in the design of this method. If more lines are drawn, more points are used to form the straight line.

5.4 Vander Veen's method (Fellenius, 1990)

Vander Veen's method is a graphical method of determining ultimate load. A series of potential ultimate loads are selected and values are calculated using Equation 2.

$$y = \ln\left(1 - \frac{Q}{Q_{ult}}\right) \qquad [2]$$

Where y is the calculated value, Q_{ult} is the ultimate load for that line, and Q is the applied load. These values are plotted against the deflection values for each Q value, and a separate line is formed for Q_{ult}. From the series of lines, a straight line is formed where the corresponding Q_{ult} is the actual ultimate load of the pile. Table 4 lists the ultimate capacities determined using this technique as well as the rated ultimate loads.

Table 4. Vander Veen's method ultimate loads

Pile ID	Rated Ultimate Load , kips (kN)	Vander Veen's method Ultimate Load , kips (kN)
1½" Pile #1	55 (245)	270 (1201)
1½" Pile #2	55 (245)	85 (378)
1¾" Pile #1	110 (490)	285 (1268)
1¾" Pile #2	110 (490)	260 (1157)
2" Pile #1	160 (710)	270 (1201)
2" Pile #2	160 (710)	400 (1779)
2¼" Pile #1	230 (1020)	290 (1290)
2¼" Pile #2	230 (1020)	240 (1068)

In each case the loads are higher than the rated loads. The difference ranged from 4 to 391 percent.

This method was computed using a spreadsheet program. However, it is very time consuming. Its effectiveness is limited by the number of readings taken during the test as well as the total test load. Tests that were not completed to loads near or above the actual ultimate load resulted in inflated values for the determined ultimate load. The ultimate loads also had to be extrapolated which means the ultimate loads are not necessarily applicable to the pile.

6 ANALYSIS

None of the alternative methods studied were effective in all situations and often required extrapolation to determine the ultimate load. The values produced by the alternative methods are so variable that any of these methods should only be used with extreme caution, if at all. Torque correlation is still the most reliable method for determining the minimum ultimate capacity of a helical pile. The load test data indicate that the torque correlation method is often conservative, and as such, the best method of determining the ultimate capacity of a pile is by carrying out site-specific load tests.

6.1 Limitations

The scope of this study is limited by certain factors. The first issue arises with a definition of ultimate load. Sometimes this is defined by maximum allowable deflections; commonly one inch, but depends on the designer. Some define ultimate load as the load where the pile is unable to maintain any more load without continual deflection. This can cause discrepancies between ultimate load capabilities of piles. Another limitation is the extent of the true capability to which the pile was tested. In order for many of these methods to be effective, the pile must be tested to a point where it no longer maintains load; this is not the case for some of the tests, whether a result of equipment, time or apparatus limitations. The limited number of tests in varying conditions is also a factor that could be further investigated. No relationship between the cohesion of the soil and the load capacity was found, but this could be due to a limited number of tests. The final limitation was the absence of tests completed on helical piles that were not installed to the maximum allowable torque. The relationship should be investigated with respect to piles tested at varying torque values.

7 CONCLUSIONS

The correlation between installation torque and the ultimate capacity of a helical pile is well documented. The empirical factor, K_T, has been generally accepted as 10 ft^{-1} (33 m-1) for solid steel, square shaft helical piles in compression. When a site has a dense underlying layer, load testing shows that a K_T value of 10 ft^{-1} (33 m-1) is often conservative and that higher loads may be achieved than the published ratings indicate based on installation torque. Determining a site-specific ultimate capacity would allow for more efficient designs using helical piles, and would provide economic benefit for users of this foundation technology.

REFERENCES

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Hoyt, R.M., and Clemence, S.P. 1989. Uplift capacity of helical anchors in soil. *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering (ISSMFE),* Rio de Janeiro, Brazil. 2: 1019-1022.