HELICAL PILE DRILLED FOUNDATIONS

DRAFT FOR REVIEW AND COMMENT

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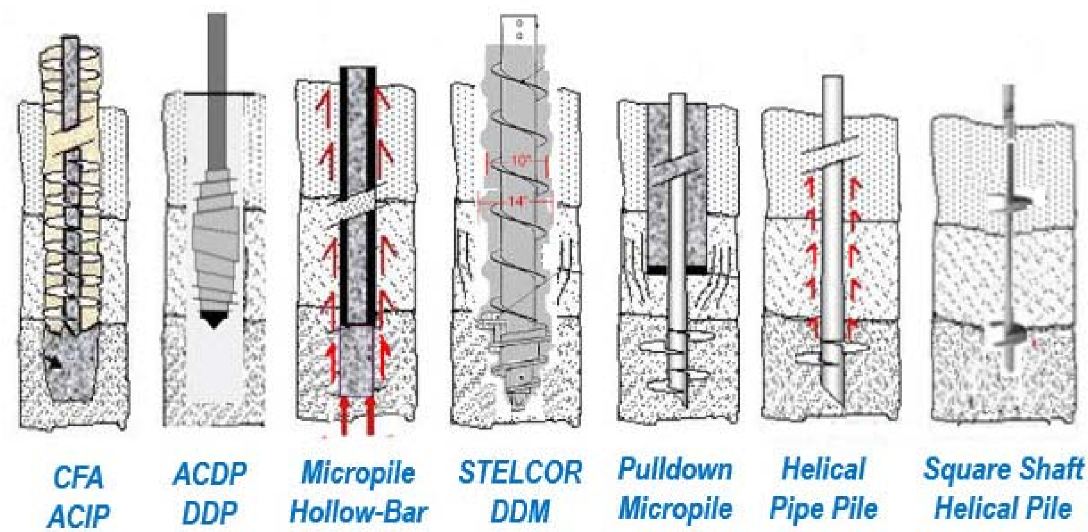
ABSTRACT

Helical pile foundations are one of the oldest types of drilled deep foundations. They were first used in England for the Maplin Sands Lighthouse in 1838, for amusement piers in 1853 and for bridges in 1883. The first use of helical screw piles in the United States was for support of lighthouses in 1843. More than 60 lighthouses along the East Coast and Gulf of Mexico were constructed on helical screw piles, some of which were in service more than 100 years.

Helical Pile foundations have been in use much longer than micropiles, which were first introduced by Fernando Lizzi in the 1950's and longer than CFA auger cast piles, which have been in use since 1966. Helical piles even predate hand dug shaft caisson foundations used by Roebling on the Brooklyn Bridge in 1870.



Helical pile design procedures over the past 10 years have gone through a remarkable evolution with the establishment of the 2007 AC358 Helical Pile Acceptance Criteria and inclusion of helical screw piles in the 2009 International Building Code (IBC). Current AC358 Acceptance Criteria applicable to shaft diameters up to 3.5 inches and 2009-2015 IBC building code requirements are presented along with advances in helical pile design and load test verification procedures. Use of the 2006 Canadian Foundation Engineering Manual (CFEM) helical pile design methodology is recommended for design of helical pile with shaft diameters greater than 4 inches. In addition, it is proposed that the 2006 CEFM helical pile design method be used as the basis for proposed new AC358 Acceptance Criteria and 2018 IBC requirements for larger diameter helical piles.

AC358 HELICAL PILE ACCEPTANCE CRITERIA

Prior to 2007, there were no International Building Code (IBC) standards which guided helical pile manufacturers in the design, fabrication, use and verification of ultimate pile capacity of helical piles. After two years of work by an ad hoc committee of the CHFM -Helical Foundation Manufacturers, final helical pile acceptance criteria were presented to the International Code Council Evaluation Services (ICC-ES). In July 2007, the International Code Council (ICC) adopted helical pile acceptance criteria to supplement requirements for pile foundations in the IBC and 1997 UBC - Uniform Building Codes.

The AC358 helical pile acceptance criteria established requirements for helical pile systems to be recognized in ICC Evaluation Service, Inc. (ICC-ES) evaluation reports in accordance with the 2006 International Building Code - Section 104.11 and 1997 Uniform Building Code - Section 104.2.8. The adopted AC358 acceptance criteria specified that the allowable capacity of a helical screw pile be based upon the following structural elements:

P1 – Pile Cap Bracket Capacity
P2 – Shaft Capacity
P3 – Helix Capacity
P4 – Soil Capacity

Helical pile capacity is calculated using conventional bearing capacity theory. Ultimate pile capacity is determined at a deflection of 10% of the average helix diameter. As an alternative, torque correlations for specific soil conditions may be determined by the following equation:

$Q = K_t\,T$ where

Q is the ultimate axial tensile or compressive soil capacity and K_t is the correlation between ultimate soil capacity and final installation torque T for a given helical pile type as shown below:

$K_t = 10\ ft^{-1}$ for 1.5 & 1.75-inch square shafts
$K_t = 9\ ft^{-1}$ for 2.875-inch round shafts
$K_t = 8\ ft^{-1}$ for 3.0-inch round shafts
$K_t = 7\ ft^{-1}$ for 3.5-inch round shafts

2009-2015 INTERNATIONAL BUILDING CODE

Due to their wide use in North America, helical piles were included in the 2009 International Building Code while the ICC-AC358 Evaluation Service Reports (ESR's) were being prepared and evaluated. The current IBC 2009-2012-2015 requirements are summarized below:

1810.3.3.1.9 Helical piles. The allowable axial design load, P_a, of helical piles shall be determined as follows:

$\boldsymbol{P_a = 0.5\ P_u}$ where P_u is the least value of:

1. Sum of the areas of the helical bearing plates times the ultimate bearing capacity of the soil or rock comprising the bearing stratum.
2. Ultimate capacity determined from well-documented correlations with installation torque.
3. Ultimate capacity determined from load tests.
4. Ultimate axial capacity of pile shaft.
5. Ultimate axial capacity of pile shaft couplings.
6. Sum of the ultimate axial capacity of helical bearing plates affixed to pile.

1810.3.5.3.3 Helical piles. Dimensions of the central shaft and the number, size and thickness of helical bearing plates shall be sufficient to support the design loads.

1810.4.11 Helical piles. Helical piles shall be installed to specified embedment depth and torsional resistance criteria as determined by a registered design professional. The torque applied during installation shall not exceed the maximum allowable installation torque of the helical pile.

2006 CFEM HELICAL PILE DESIGN

Canadian experience with the design and installation of helical piles resulted in the adoption of the following helical pile design method in the CFEM-Canadian Foundation Engineering Manual (CFEM, 2006).

The total capacity of a helical pile or anchor equals the bearing capacity of the soil applied to the individual helical bearing plates and in the case of larger diameter piles the skin of the shaft is calculated as follows:

$$\mathbf{R = Q_t + Q_f} \qquad \text{where}$$

R = Total capacity of the helical pile or anchor,
Q_t = Total multi-helix pile capacity, and
Q_f = Capacity due to pile shaft skin friction

$$\mathbf{Q_t = \sum Q_h} \qquad \text{where}$$

$$\mathbf{Q_h = A_h\,(s_u N_c + \gamma D_h N_q + 0.5\gamma B N_\gamma)} \qquad \text{and}$$

Q_h = Individual helix bearing capacity
A_h = Projected helix area,
S_u = Undrained shear strength of the soil,
γ = Unit weight of the soil,
D_b = Depth to the helical bearing plate,
B = Diameter of the helical plate, and
N_c, N_q and N_γ = Bearing capacity factors fort local shear conditions

The above Q_h bearing capacity equation is only applicable when the helical bearing plates are spaced far enough apart, at least 3 times the diameter of the largest helix, to avoid overlapping stress zones.

In cases involving overlapping stress zones, the multi-helix capacity Qt can be determined by computing the bearing capacity of the bottom plate, and the cylindrical shear capacity developed between the upper and lower helix plate(s) by using the following shaft skin friction formula with the appropriate revision of pile shaft diameter to effective helix diameter.

The skin friction along the pile shaft typically is calculated as follows and is not considered along the shaft between the upper and lower helix plates. Shaft friction is ignored unless the shaft diameter is at least 4 inches:

$$\mathbf{Q_f = \sum(\pi D\ f_s\ \Delta L_f)} \quad \text{where}$$

Q_f = Frictional pile shaft resistance and/or soil cylinder between the upper and lower plates.
D = Pile shaft diameter and/or effective helix diameter
f_s = Sum of friction adhesion between the soil and pile, and
ΔL_f = Incremental pile shaft length or soil cylinder over which πD and fs are constant.

2006 CFEM HELICAL PILE TORQUE CORRELATIONS

An estimate of the helical pile capacity may be achieved through monitoring of installation torque. Recording of installation torque also serves as a quality control (QC) step identifying piles that did not achieve the expected installation torque and may require load testing. The relationship between helical pile capacity and installation torque was developed based upon helical pile pullout tension tests using the following empirical equation:

$$\mathbf{Q_u = K_t \times T} \quad \text{where}$$

Qu = the ultimate capacity of the helical pile,
K_t = Empirical torque correlation factor, and
T = Average installation torque.

Installation torque is primarily a function of the frictional resistance along the shaft, and to a lesser extent the frictional resistance along the top and bottom surfaces of the helix bearing plates. The value of K_t may range from 3/ft to 20/ft if T is recorded in ft-lbs. For small diameter square shaft anchors less than 3 inches, the K_t was found to range from 10/ft to 12/ft with the value of 10/ft recommended as the default value. For round pipe shafts, default Kt values are 9/ft for 2.875 in., 8/ft for 3.0 in., and 7/ft for 3.5 in shaft diameters.

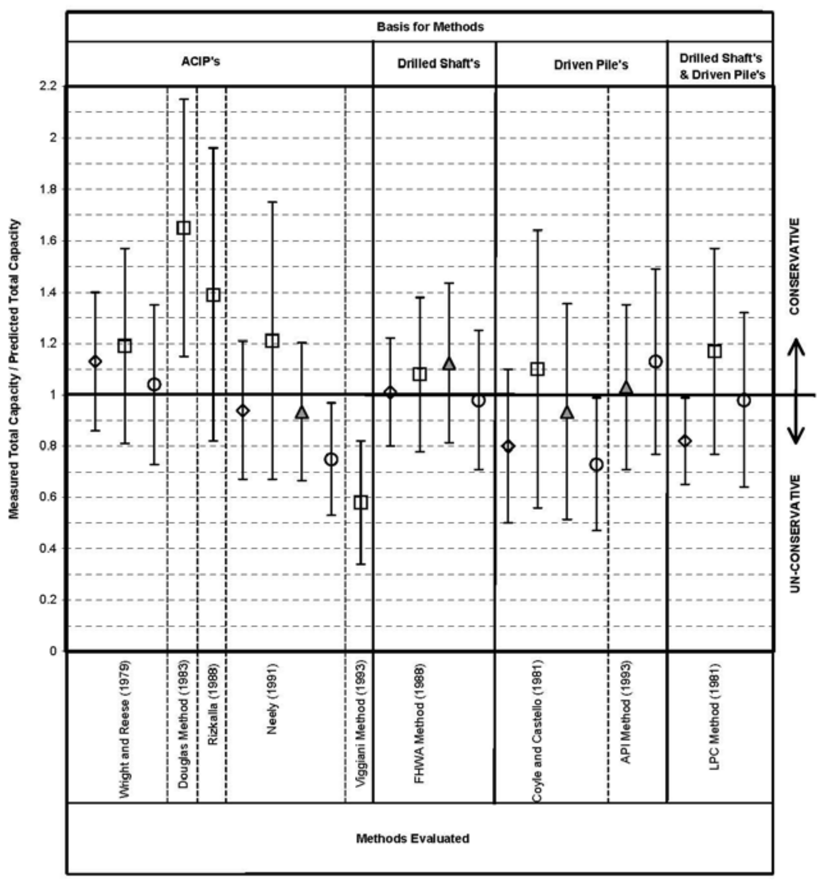
Torque monitoring tools provide a suitable method of production control during installation and should be used by the engineer to specify a required installation torque for quality control.

ULTIMATE PILE CAPACITY

The evaluation of ultimate pile bearing capacity of both driven and drilled pile foundations is based upon extensions of the bearing capacity theory developed for shallow foundations which was pioneered by Terzaghi (1943). Skempton (1959) and Meyerhof (1976) also provided the basis for estimating the bearing capacity of a deep foundation. Unfortunately methods proposed by all past and current researchers involve using empirical "N" bearing capacity factors to take into account the scale effect between shallow and deep foundations. It should be recognized that:

- The Terzaghi triple "N" bearing capacity equation is more than 50 years old
- Numerous variations of the "N" coefficients have since been published
- The equation was originally developed for shallow foundations

Despite all the uncertainties, use of pile design methods based upon the Terzaghi (1943) bearing capacity theory coupled with local experience of foundation engineers remains the basis for deep foundation pile design (Zhang, 1999). It should be recognized that numerous pile design methods used today will often yield a range of estimated ultimate pile capacity as shown below (FHWA GEC8, 2007).



Comparison of Study Results – Axial Capacity in Cohesionless Soils

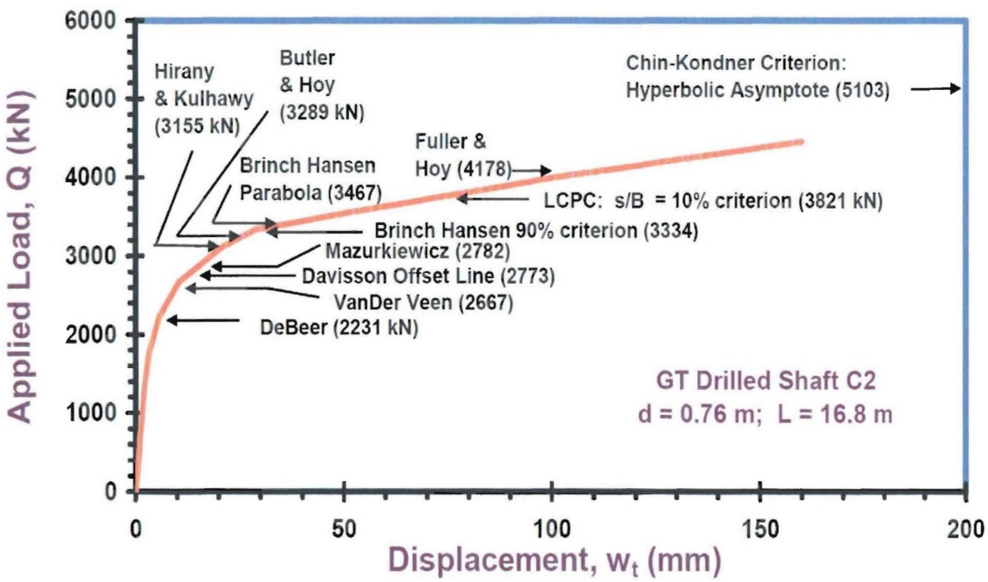
FHWA CFA Pile Design & Construction - gec8

ULTIMATE PILE CAPACITY LOAD TEST VERIFICATION

Load testing of piles is the most positive method of determining ultimate pile capacity, load-deflection (serviceability) behavior, and verification of design assumptions. The actual load test procedure used and the interpretation of method of ultimate pile capacity are two factors which can significantly the determination of ultimate pile capacity.

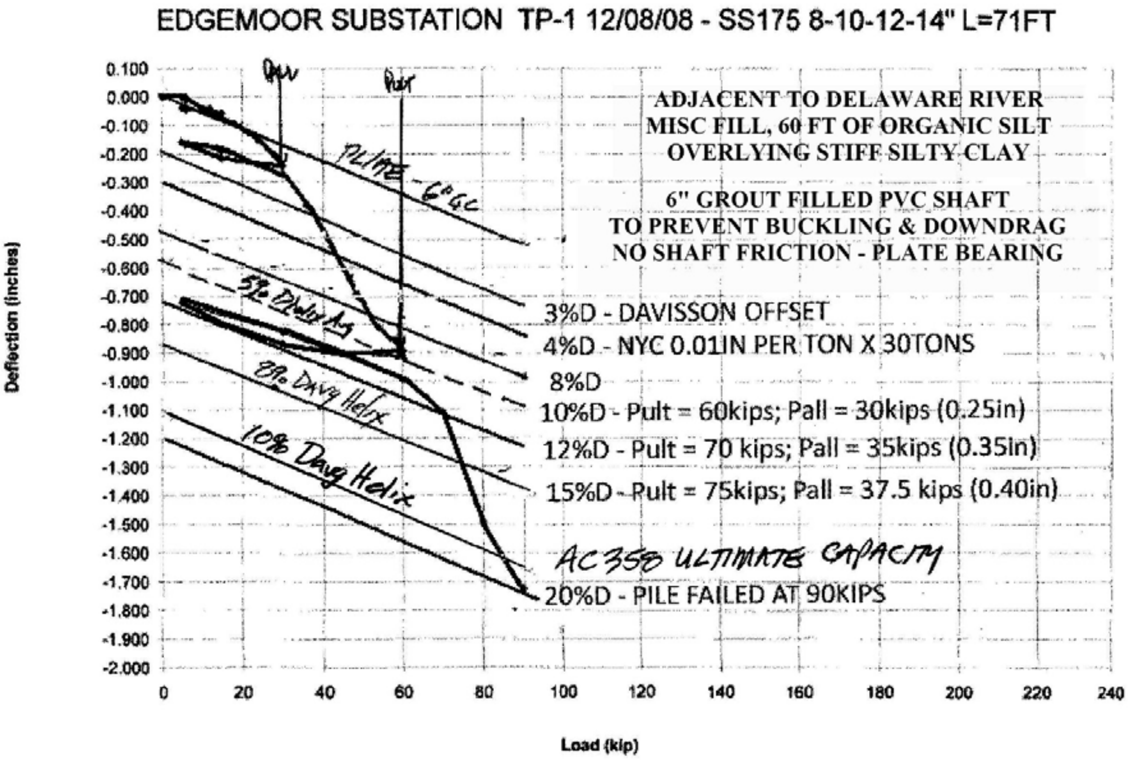
Load Test Procedures - Lutenegger (2013) provides a detailed overview of the ASTM D1143 load test standard and it's evolution over the years. Variations in the selected loading sequence and the time interval of readings can significantly influence load test results.

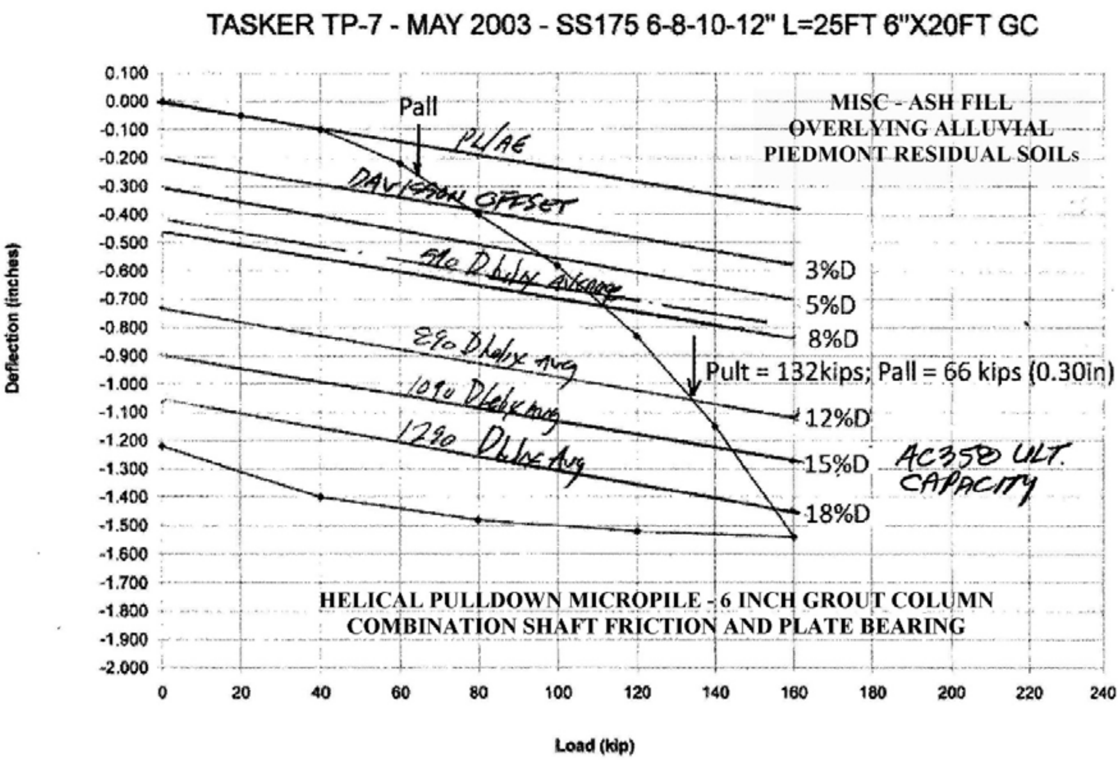
Interpretation of Ultimate Pile Capacity - Significant differences in interpreted capacity result from the number of methods available for the analysis of load testing data. Hirany & Kuhlawy (1988) identified over 40 different procedures available to provide an interpretation of failure load. Nearly all require some type of graphical manipulation of the load test data to provide an ultimate capacity. An example of the wide range of interpreted ultimate pile capacity for an instrumented drilled test load testing program is shown below (FHWA, 1993).



Most helical pile load tests do not display a "plunging" type failure behavior unless the displacements are taken to very high values and then may still not plunge. In the absence of plunging failure, Lutenegger (2013) recommends using a definition of failure that does not require a graphical method and is based upon a failure load that corresponds to a fixed relative displacement. AC358 Helical Pile Acceptance Criteria defines ultimate capacity as the load producing a net displacement of 10% of the average helix diameter. Experience with large diameter helical pile load tests and numerical modeling indicates that ultimate capacity should be defined as the load which produces a settlement of the 5% (Sakr, 2011), (Elsherbiny and El Naggar, 2013) and Padros and Ibarra (2013).

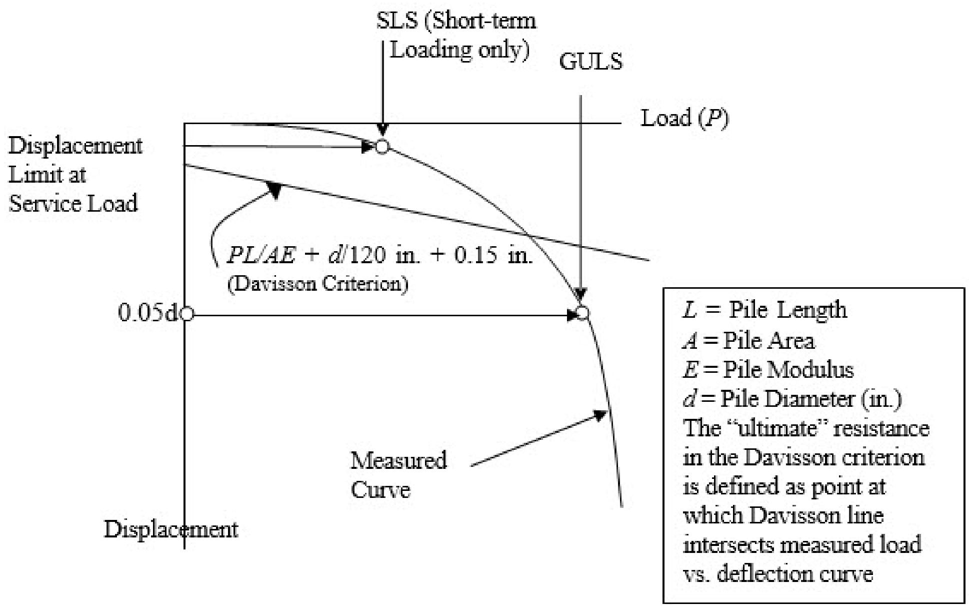
Two annotated helical pile load tests are shown below which demonstrates the flexibility of establishing ultimate pile capacity at a given relative deflection to produce an acceptable settlement at design load based upon helix and shaft diameter (Perlow, 2011).





DRILLED FOUNDATION LIMIT STATES

<u>Geotechnical Ultimate Limit State (GULS)</u> – Drilled pile foundations should have a load resistance that is greater than the expected (service) loads by an adequate margin to provide a required level of safety (safety factor). For axial compressive loads of drilled foundations, the GULS is often defined as the load resistance at a displacement equal to a percentage of the pile diameter (or average helix diameter) in an axial load static load test as shown below.



GULS and Short-Term SLS for Axial Load on a Single CFA Pile

The GULS is often referenced using the words "capacity" or "failure" which is an unfortunate choice of words because no collapse or condition of plunging may exist at the GULS and the pile may have the capacity to support additional load beyond the GULS. The state of deformation associated with the GULS should not be confused with deformations at service loads.

<u>Service Limit State (SLS)</u> – The pile should undergo deformations at service loads that are within the tolerable limits appropriate to the structure which typically is on the order of 0.25 to 0.33 inches for occupied buildings and on the order 0.5 inches or more for other non-critical structures. The actual definition of the service limits should be determined by a rational assessment of the sensitivity of the structure to deformations. Short-term deformations for transient loading are a function of the mobilization of pile resistance as determined from the load – deflection curve shown previously above. It should be recognized that long-term settlements under structural loads are a function of group settlements and should be computed accordingly.

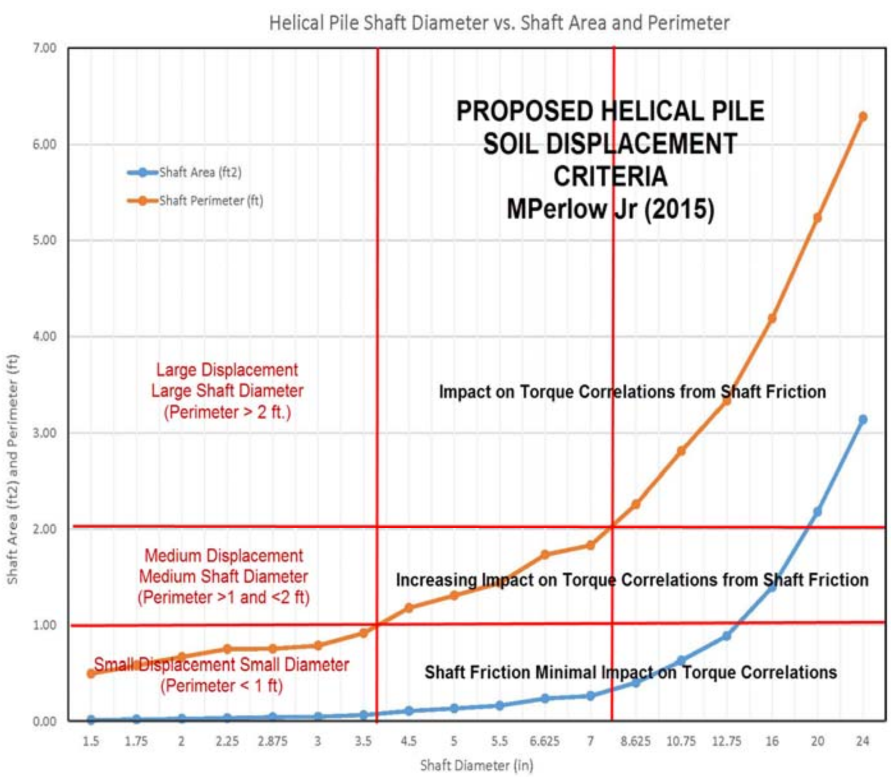
<u>Structural Ultimate Limit State (SULS)</u> – The pile foundation must have sufficient structural capacity when the pile is subjected to flexural loads such that structural yielding of the pile does not occur. The SULS provides a second service limit state. Typically building codes will define the maximum allowable structural capacity of the pile foundation.

LARGE & SMALL DIAMETER HELICAL PILE
AC358 ACCEPTANCE CRITERIA & IBC 2018 UPDATES

The helical pile industry finds itself at a crossroad. The development of the AC358 Acceptance Criteria for small diameter helical piles provided standard design and performance criteria for the helical pile industry. As installation equipment and procedures continue to improve, the installation of larger diameter helical pile is increasing rapidly.

The ICC International Code Council Evaluation Service has recognized the growing importance of large diameter helical piles and has requested input from industry and the DFI Helical Piles & Tiebacks Committee on new acceptance criteria for large diameter helical pile design and performance. The following is offered as a roadmap and starting point for development of AC358 acceptance criteria and IBC 2018 changes for large and small diameter helical piles.

<u>Skin Friction Contribution to Ultimate Pile Capacity</u> - As helical pile shaft diameters increase, the amount of soil displaced and disturbed increases along with the contribution of shaft friction to ultimate pile capacity. As shown below, the perimeter of the small (< 4 inches) diameter helical piles covered by the current AC358 Acceptance Criteria have a perimeter of less than 1 sf. The large diameter (> 8 inches) helical piles have perimeter values ranging from 2 ft. to 6 ft. or more indicating that the contribution of skin friction to ultimate pile capacity increases significantly with increasing shaft diameter.



The 2006 CFEM helical pile design method offers a simple design methodology that adds shaft skin friction to helical plate bearing capacity theory. It also provides a rational basis for the current AC358 criteria which excludes shaft friction for pile diameters less than 4 inches.

<u>GULS Ultimate Pile Capacity</u> - Use of a GULS (Geotechnical Ultimate Limit State) based upon helix diameter ranging from 10% for small diameter to 5% for large diameter shafts should be considered to define the ultimate pile capacity that produces acceptable settlements at working loads (SLS). IBC Section 1810.3.3.1.2 on Load Tests requires that ultimate axial pile capacity be determined by a registered engineer with consideration given to the total and differential settlement at design working loads. The current 2009-2015 IBC also requires the allowable load be no more than one-half of the ultimate axial load capacity of the load test as determined by one of the following methods listed in Section 1810.3.3.1.3:

1. Davisson Offset Limit.
2. Brinch-Hansen 90% Criterion.
3. Butler-Hoy Criterion.
4. Methods approved by code officials **(ICC-AC358 5%-10% GULS Limit States)**

It is proposed that upcoming changes to the 2018 IBC include the addition of GULS and SLS criteria in Section 1810.3.3.1.2 so it can be considered a "Method approved by code officials". It should be recognized that current AC358 acceptance criteria is based upon an ultimate pile capacity at a deflection 10% helix diameter which is in fact a GULS. As shown in the previous two annotated helical pile load tests, a GULS can be established based upon a percentage of average helix OR shaft diameter to produce an ultimate pile capacity with acceptable settlement at the SLS design working loads.

<u>Disturbance Caused by Soil Displacement</u> - Due to the increased soil displacement and corresponding disturbance that occurs with larger diameter shafts and helix plates, the efficiency of successive multi-helix plates can be reduced as compared to the lead helix. It is recommend that a reduction in shear strength and/or introduction of a helix efficiency factor be considered for multi-helix pile configurations as proposed by Elsherbiny and El Naggar (2013) and Dr. Alan Lutenegger in his 2015 Quick Design Guide for Screw Piles and Helical Anchors in Soils Version 1.0 published by the International Society for Helical Foundations (Lutenegger, 2015).

REVIEW COMMENTS REQUESTED

The intent of this submittal to HPW is to offer a single Helical Pile Design Method for all shaft diameters that is based upon the 2006 Canadian Foundation Engineering Manual for use in the development of updated AC358 Acceptance Criteria and upcoming revisions of the 2018 IBC. The use of a Geotechnical Ultimate Limit State (GULS) is also proposed for inclusion into the 2018 IBC as an alternate method for determining ultimate pile capacity from load tests. Finally, use of a simple helix efficiency factor to account for potential soil disturbance from trailing helix plates in a multi-helix is proposed.

Industry experts, engineers, manufacturers, installers, distributors, and academia are invited to submit comments on the above to HPW, the DFI Helical Pile Tiebacks Committee and the author. The contents of this submittal are excerpts of a DFI Journal Paper entitled Helical Pile Drilled Foundation Design which is in final preparation and will be submitted in December.

Readers with questions or comments can reach Mike at mike@perlomp.com or 267-664-3250.

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