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# Deflection of Helical Piles: A Load Test Database Review

by

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**ABSTRACT:** In most cases helical piles generate almost all of their capacity by end bearing (i.e. bearing of the helices at depth). Based upon historical experience, it is usually expected that net deflections at working loads will be around one-half inch or less which is acceptable for most structures. Over the last few years, data from over 202 full scale tension and compression load tests has been collected using the methods described in Acceptance Criteria for Helical Foundation Systems and Devices (AC358, 2007). Measured helical pile deflections at working loads in clay, sand, and bedrock soils will be presented.

## INTRODUCTION

Helical Piles are a useful tool in the deep foundation engineering tool belt. Many studies have been published regarding the capacity of these devices and correlations of torque to capacity. Few studies have been conducted that discuss the serviceability or amount of deflection typically associated with these types of foundations. The goal of this paper is to share the results of recent compression and tension load tests on helical piles and to provide a summary of measured deflections. This paper contains a summary of test procedures, a review of different load test interpretation methods, a summary of measured pile deflections, and a discussion of tolerable deflections in design and construction.

## TEST PROGRAM

A study was conducted on a load test database consisting of 93 compression and 109 tension tests. The load tests were performed by an IAS Accredited laboratory, CTL|Thompson, Inc. The tests were conducted on behalf of five different helical pile manufacturing companies seeking ICC-ES evaluation reports under the criteria set forth by ICC-Evaluation Services acceptance criteria AC358.

Test specimen included 1.5" and 1.75" square-shaft helical piles as well as 2-7/8", 3", and 3.5" diameter round-shaft helical piles. Helical piles were installed in sand, clay, and weathered bedrock primarily in sites along the Front Range of Colorado. Final installation torque varied form under 1 ft-kip to 13 ft-kip. Installation depth varied. At a minimum, helical piles were installed to a minimum embedment equal to 12 times the average helix diameter for tension tests.

**TESTING PROCEEDURS**

Helical pile static compression and tension load tests were conducted in accordance with ASTM D1143 and ASTM D3698, respectively. Static compression load tests were performed using a load frame constructed over the test pile. Reaction piles, consisting of four helical anchors were installed a minimum clear distance of 7 feet [2 m] away from the test pile. The photograph in Fig. 1 shows a typical set-up of equipment for compression load testing. Tension load tests were performed on vertical piles using twin reaction beams spanning over wood dunnage bearing on ground.

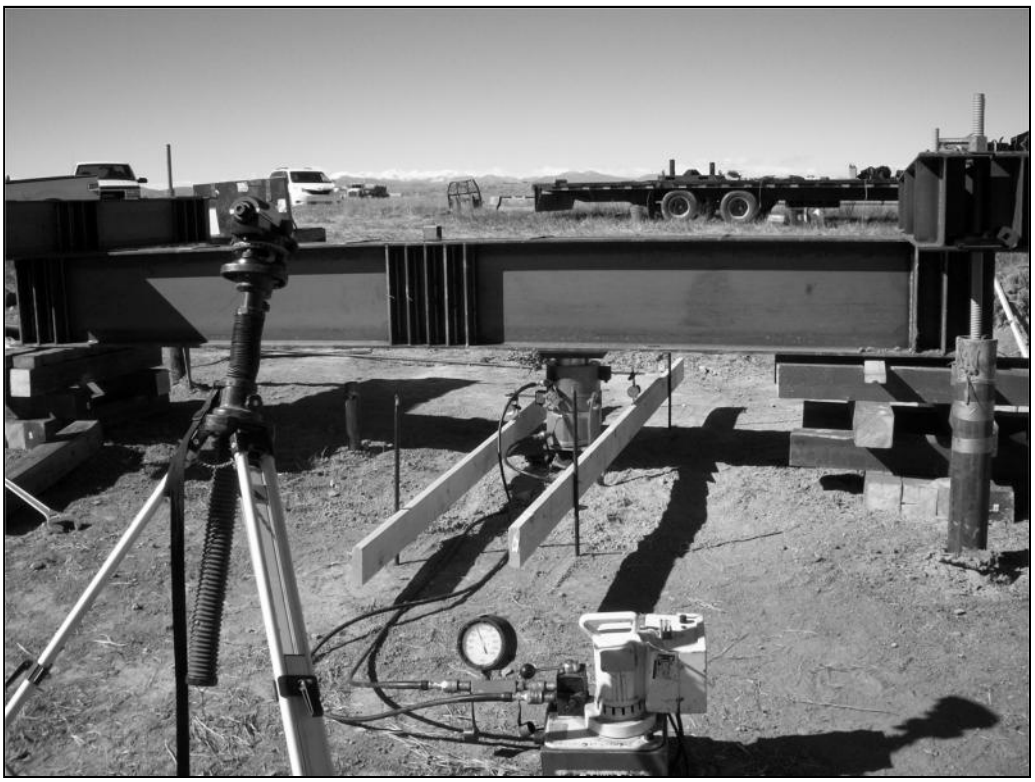

**Fig. 1 Example Compression Load Test Equipment**

In all tests, twin dial gage extensometers were used as a primary means to measure pile deflection. The dial gages were located at opposite sides of the pile cap. The dial gages were affixed to reference beams supported at a significant distance away from the top of the pile. A hydraulic ram was centered over the test pile. Hydraulic pressure was used to measure applied loads. The ram, pressure gauge, and hydraulic pump are calibrated as a unit. An engineer's scale was affixed to the side of the pile. The engineer's scale was monitored using a surveyors transit as a secondary means of pile deflection measurement.

ASTM D1143 and D3689 contain several different loading procedures for static axial compressive and tensile load testing of piles. The loading procedures contained in both standards are identical with the exception of the frequency of load, time, and displacement readings. The various procedures contained in both ASTM documents include standard, cyclic, quick, excess load, constant time intervals, constant rate of penetration, and constant settlement increments.

Standard load test procedures involve long hold times is considered for helical piles and helical anchors when pile deflections need to be verified to a high degree of accuracy or when long-term creep is suspected. Cyclic load testing involves loading and unloading the pile multiple times and is considered when helical piles or helical anchors are expected to support fluctuating loads. The excess load test procedure involves loading and unloading the pile following the standard procedure. Then the pile is reloaded to failure. Excess load test procedures to prove the pile can support 200% of the design load and to find the ultimate capacity at failure.

Helical piles generally react quickly to applied loads. The most frequently applied load test procedure for helical piles is the quick load test. The quick load test procedure is permitted by ICC-ES AC358 and was used for all tests in this study. The quick load test involves loading the pile in 10% to 15% increments until plunging failure or until the capacity of the load frame is reached, whichever occurs first. In the 2002 version of the standard, each load increment is held for 2.5 mins. Readings are taken before and after each load increment. The final test load is held for 5 mins without further jacking. After the hold period, all loads are removed from the pile in one decrement and rebound readings are taken at 0, 2.5, and 5 mins after unloading. In the 2007 standard, each increment is held for 4 mins and readings are taken at 30 sec, 1 min, 2 min, and 4 min. There is no additional hold time at the final increment. Loads are removed in 25% decrements. Although the ASTM procedure does not specifically address the issue, a setting load of 10% to 15% of the design load was applied to each helical pile prior to taking initial readings.

Load tests in this study were run over the course of many years; they were performed using the quick test method in accordance with both the 2002 and 2007 standards. The quick test procedure is preferred by contractors, because pile loading and unloading can be completed in a few hours compared to several days for the standard and cyclic load test procedures. The quick test is superior to the standard test from technical, practical, and economic views (Fellenius, 1990). Test piles were tested were generally tested within 24 hours after installation.

## INTERPRETATION METHODS

The capacity determined from pile load testing depends on the method of load test interpretation. There are several methods of which the helical pile designer needs to be aware. The International Building Code (2009), Section 1810.3.3.1.3 recognizes the Davisson Offset Method, Hansen 90% Method, Butler-Hoy Criterion, or other methods approved by the building official. The "other" method used with helical piles in this study is described in ICC-ES

Document AC358 and is often termed the Modified Davisson Method. Each of these methods of load test interpretation is described here.

The original Davisson Offset Method offers a way of finding the point where shaft adhesion is fully mobilized by compensating for pile stiffness (Fellenius, 2001). The method consists of drawing a line with a slope equal to the elastic lengthening/shortening of the pile offset by a value of 0.15 inch [4 mm] plus a factor equal to the diameter of the pile divided by 120 (Davisson, 1972). For a helical pile with average helix diameter of 12", the Davisson offset is 0.15" + 0.10" = 0.25". The point at which this offset line intersects the load-deflection curve is taken as failure. The original Davisson offset method significantly underestimates the ultimate capacity of end bearing piles, because they require much greater deflection to mobilize their full strength. The original Davisson method is more appropriate for friction piles and when making correlations with wave equation analysis of driven piles.

The Butler-Hoy Criterion (Butler and Hoy, 1977) and Hansen 90% Method (Brinch-Hansen, 1963) are graphical analysis of the load-deflection curve. The Butler-Hoy Criterion defines pile failure as the load at the intersection of a tangent parallel to the initial load curve and a line sloping 0.025 inch/kip that is tangent to the load curve. In order to remove judgment on the part of the drafts person, Fellenius (1980) suggests that a line matching the slope of the rebound load-displacement curve for the pile test be used instead of a tangent parallel to the initial load curve. The Butler-Hoy Criterion is useful when one cannot apply the Davisson Offset Method because elastic modulus or mobilized length are not well known (Fellenius, 1990). The Butler-Hoy Criterion is excessively conservative and inappropriate for lightly loaded piles because the shape of the load-deflection curve for a pile designed with low capacity is much flatter than the curve for a higher capacity pile with the same total deflection limit.

According to the Hansen 90% Method, failure is where the deflection at that load is two times greater than the deflection at 90% of that load. This point is found graphically through trial and error. The Hansen 90% method generally provides an indication of the yield point. The method works well for friction piles and for end bearing piles on hard stratum that exhibit a load-deflection curve with definite yield point. Helical piles and other end bearing piles in medium sands or normally consolidated clay strata exhibit a curvilinear shape without a definite yield point. Often, the Hansen 90% criteria is never reached during a load test on a helical pile.

The Modified Davisson Method is most often used for load test interpretation of helical piles. This method is prescribed in ICC-ES AC358. In this method, failure is defined as the load causing a net deflection equal to 10% times the average helical bearing plate diameter (ICC-ES, 2007). Net deflection is defined as the total deflection at the pile head minus elastic shortening or lengthening of the shaft. The elastic change in shaft length may be computed from the well-known equation PL/AE, where P is the load applied to the pile, L is the length of pile shaft, A is the cross-sectional area of the pile shaft, and E is the modulus of elasticity of the shaft steel. Elastic shortening/lengthening also may be determined from the rebound of the pile head upon removal of the axial load. Often the rebound deflection is slightly more than theoretical shaft elongation, PL/AE, because the helices also exhibit some elastic deflection and rebound. It is conservative to use PL/AE in this method. The Modified Davisson Method given in AC358 was used for interpretation of the tests in this study.

An example of a load-deflection curve for a static compression test on a helical pile is shown in Fig. 2. Notice the curvilinear appearance of the curve and the lack of definite yield point. This shape of load-displacement curve is typical of helical pile load tests. In this figure, the failure limits defined by the original Davisson Offset Method, the Butler-Hoy Criterion, the Hanson 90% Method, and the Modified Davisson Method. The data represented by diamond symbols in the figure were obtained from an actual load test on a helical pile with 3-inch [76 mm] diameter shaft and three helical bearing plates with 12-inch [305 mm] average diameter. The pile bottomed in stiff glacial till and had a final installation torque of 4,500 ft-lbs. The inclined dashed lines in the figure were drawn using PL/AE.

For the example load test in Fig. 2, the method of interpretation resulting in the lowest failure load of 10 kips is the Butler-Hoy Criterion. The reason is that the loads are so low in this example that the load curve reaches the limiting Butler-Hoy slope within the first approximately 1/8" of total pile movement. The second most conservative interpretation shown in the figure is the Davisson Offset Method which yields a failure load of 18 kips for the same load test. This point is where the adhesion between the helical pile shaft and the soil reaches a limit state and the helical end bearing elements begin to carry a majority of the load. As can be seen, the original Davisson Offset Method severely underestimates the capacity of the example helical pile. The Modified Davisson Method gives a failure load of 32 kips for the same load test. This method provides a more reasonable estimate of the maximum capacity of a helical pile. The maximum deflection can be computed ahead of time when planning load tests. With regard to the Hansen 90% Method, as can be seen in Fig. 2, the load test shown did not yet reach failure based on this method. Extrapolation of the data suggests a failure load of 39 kips based on the Hansen 90% Method.

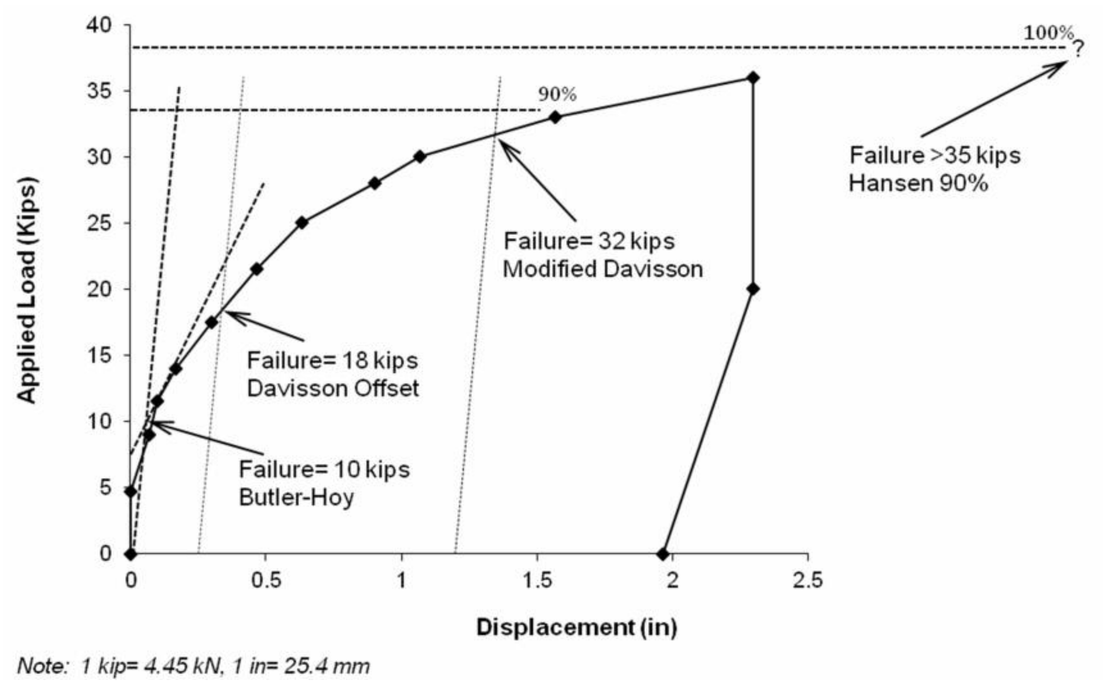


**Fig. 2 Example Helical Pile Load-Deflection Curve (Modified from Perko, 2009)**

## SUMMARY OF DEFLECTION RESULTS

A summary of the results of the deflection measured in static load tests included in this database review are provided in the following bar graphs. These graphs were briefly introduced by Cherry (2012). In all tests, the ultimate capacity of the pile was taken as the "failure" load as defined by the Modified Davisson Criteria. The working capacity of the piles was taken as the ultimate capacity divided by a factor of safety of 2.0.

As can be seen in Figs. 3 and 4, the mean "total" and "net" deflection of helical piles in the load test database at working loads is 0.31 in and 0.23 in, respectively. Net deflection is defined as the total deflection minus the theoretical elastic shorting/lengthening of the helical pile shaft. Total deflection is affected by the helical pile shaft length. Net deflections are more indicative of the interaction between the helical bearing plates and the ground. These two figures represent all compression and tension test data.

In order to evaluate the effect of bearing in different strata, the load test data were separated into groups consisting of load tests in clay, sand, and weathered bedrock. The deflection distribution for these groups are shown in Figs. 5, 6, and 7. Pile deflections at working capacity was lower in clay and weathered bedrock than in sand. The clay soils in this study were stiff and over-consolidated. Results can be expected to vary for normally consolidated clays and silts.

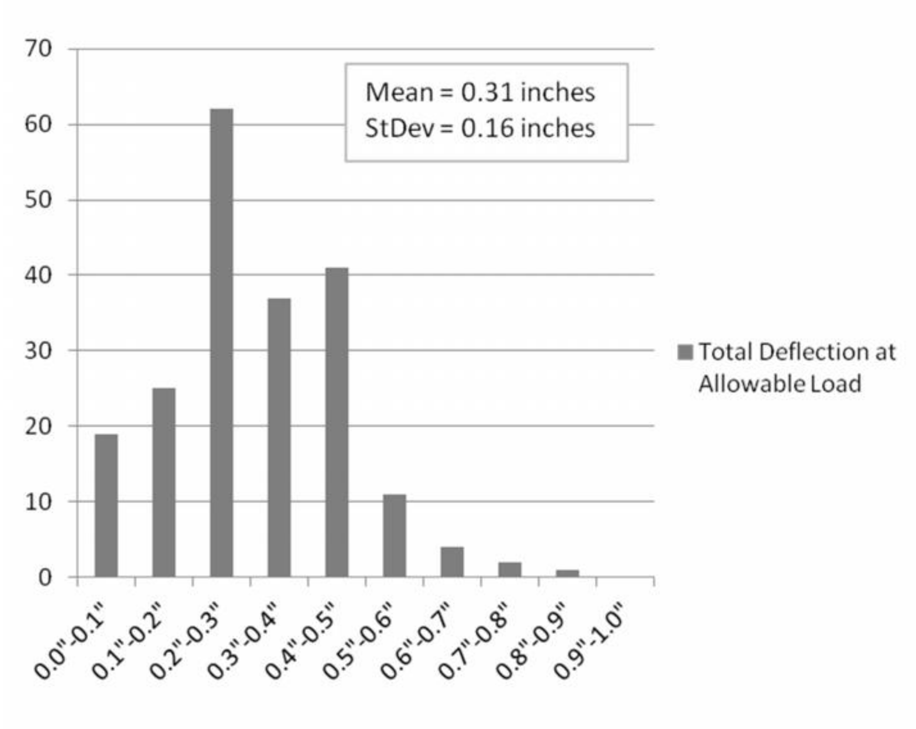


**Fig. 3 Total Deflection at Working Capacity for All Tests - Compression and Tension Tests Combined**

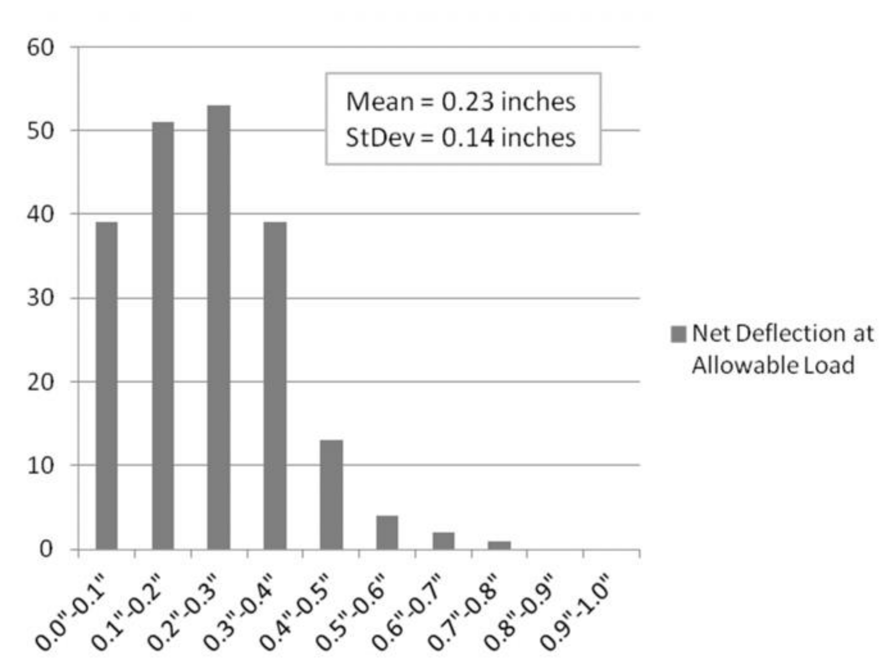


**Fig. 4 Net Deflection at Working Capacity for All Tests - Compression and Tension Tests Combined**

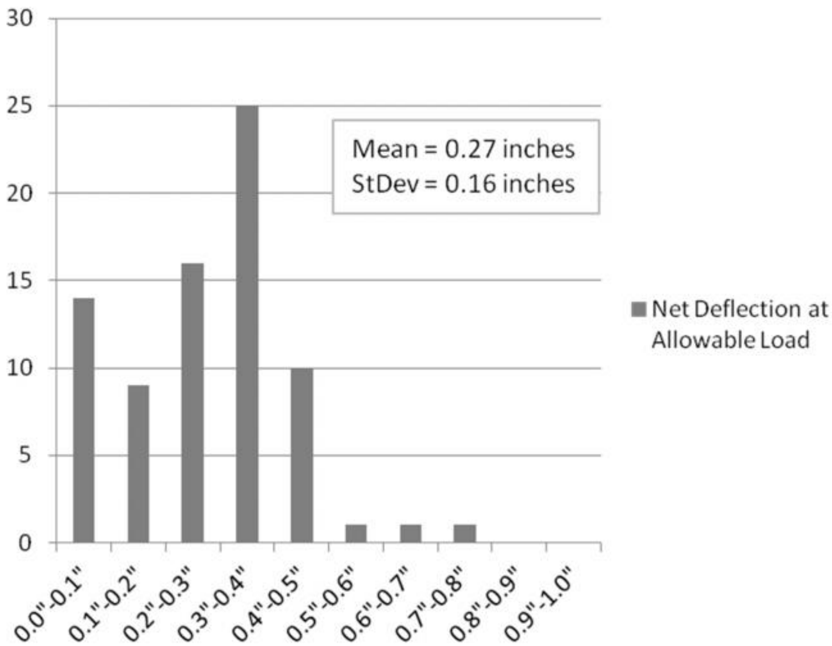


**Fig. 5 Net Deflection at Working Capacity in Sand – Compression and Tension Tests Combined**

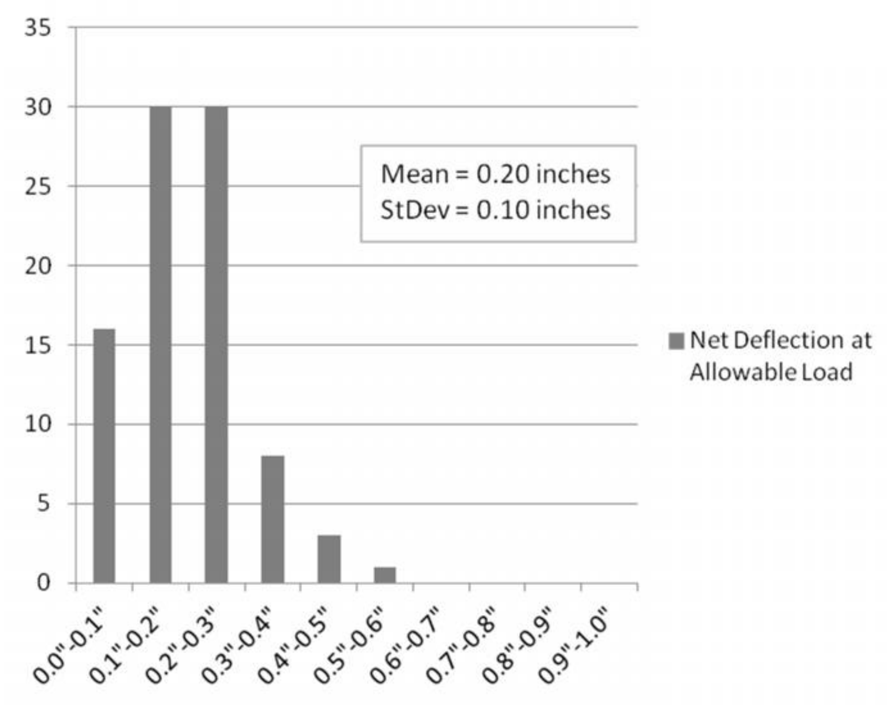


**Fig. 6 Net Deflection at Working Capacity in Clay - Compression and Tension Tests Combined**

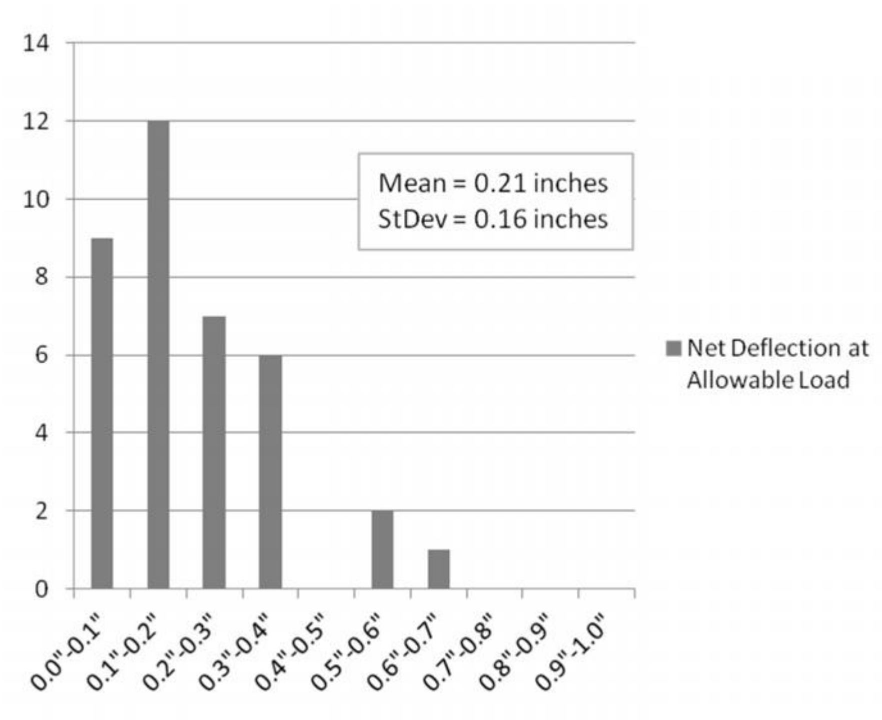


**Fig. 7 Net Deflection at Working Capacity in Weathered Bedrock - Compression and Tension Combined**

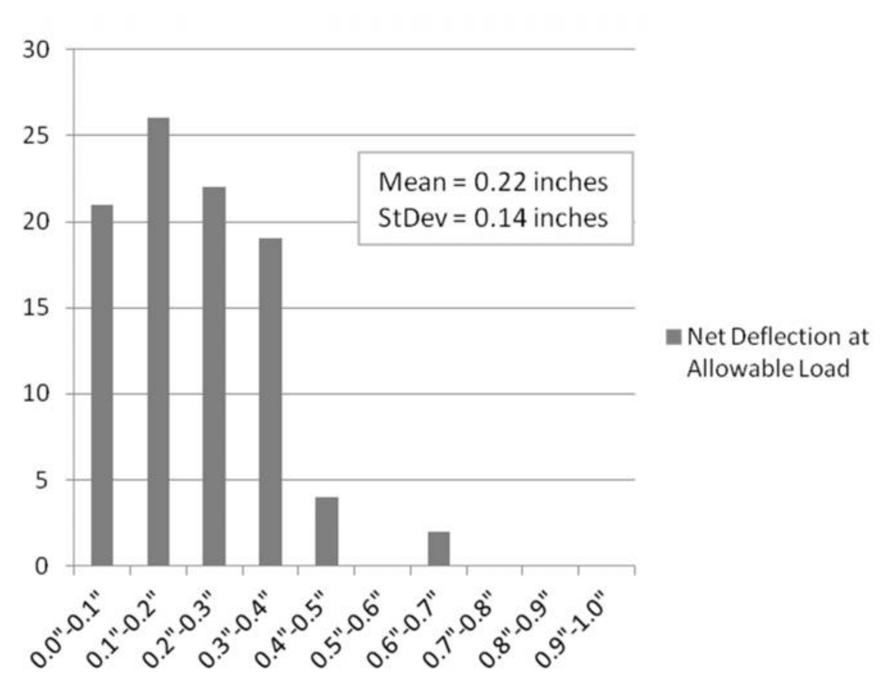


**Fig. 8 Net Deflection at Working Capacity for All Tests - Compression Only**

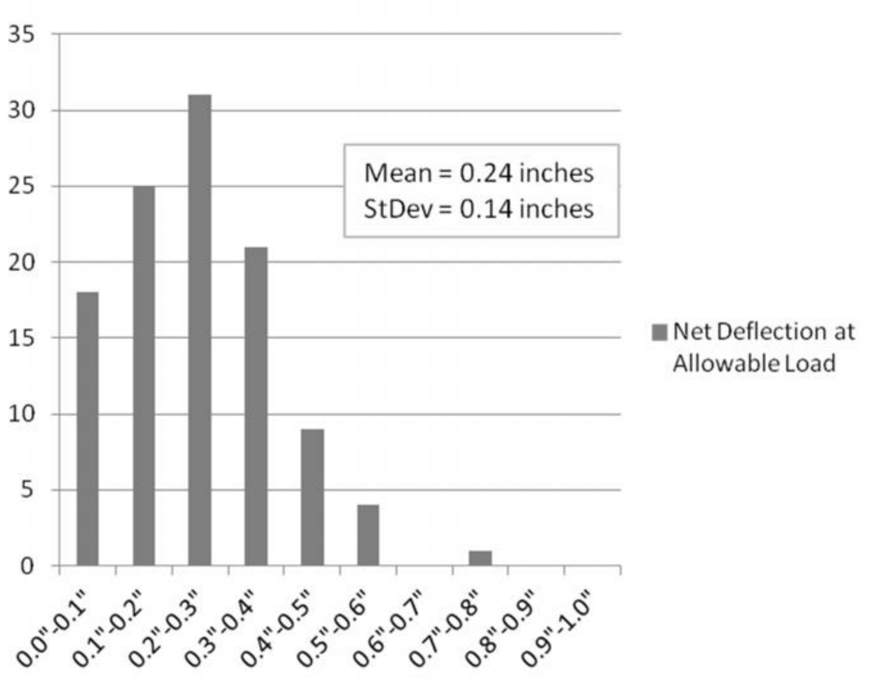


**Fig. 9 Net Deflection at Working Capacity for All Tests - Tension Only**

As another way to view the load test data, tension and compression tests were separated. The distribution of deflections measured at working capacity for compression only are shown in Fig. 8. The distribution for tension only are shown in Fig. 9. The mean net deflection for compression and tension tests were 0.22" and 0.24", respectively. One reason the mean deflection is slightly higher for tension tests may be disturbance of the ground as the helical bearing plates pass through this zone of soil. Overall, the mean deflections between compression and tension tests are very close. Helical piles appear to perform similar in tension and compression with respect to deflection at working loads.

A summary of statistical data from all tests and Figs. 3 through 9 are given in the table below. The mean values provided in Table 1 can be used by helical pile designers to approximate average helical pile deflection in different conditions. Standard deviations can be used to estimate probability of being within those deflections.

| Bearing Material | Compression (93 Tests) | | Tension (109 Tests) | | Compression & Tension (202 Tests) | |
|---|---|---|---|---|---|---|
| | **Mean (in)** | **Standard Deviation** | **Mean (in)** | **Standard Deviation** | **Mean (in)** | **Standard Deviation** |
| **All (202 tests)** | **0.22** | **0.14** | **0.24** | **0.14** | **0.23** | **0.14** |
| **Sand (76 Tests)** | **0.27** | **0.15** | **0.27** | **0.17** | **0.27** | **0.16** |
| **Clay (89 Tests)** | **0.17** | **0.10** | **0.21** | **0.11** | **0.20** | **0.10** |
| **Wx Bedrock (37 Tests)** | **0.19** | **0.16** | **0.22** | **0.16** | **0.21** | **0.16** |

**Table 1. Summary of Deflection at Working Loads**

## TOLERABLE DEFLECTION

How much pile deflection is too much? An historic method is to limit total pile movement at the ultimate capacity to 10% of the pile diameter (Fellenius, 1990) as in the Modified Davisson Method. Maximum deflection limits at ultimate capacity between 3/4 inch [19 mm] and 1.5 inch [38 mm] are published in some local building codes. Another common practice is to limit the deflection at the design load rather than the ultimate load. Typical values range from 3/8 inch [10 mm] to 1 inch [25 mm].

The maximum deflection should depend on the sensitivity of the structure to movement, desired foundation rigidity, and local practice. Deflection at working capacity is more important to structure performance than deflection at ultimate failure loads.

Fleming, Weltman, Randolph, and Elson (1985) state that the adhesion along a pile shaft is mobilized in very small deformations typically less than 0.2” [5 mm]. End bearing resistance is not fully mobilized until large settlements occur, up to 20% of the base diameter in coarse grain soils and 10% of the base diameter in fine grain soils. Due to their unique shape with slender shafts and large baring elements, ordinary (non-grouted) helical piles behave more akin to end bearing piles. As such, the method of load test interpretation used with helical piles should be one that allows for full mobilization of end bearing resistance. Otherwise the true capacity of helical piles will be underestimated.

## CONCLUSIONS

The basic definition of ultimate capacity is the highest load that can be applied to a pile or anchor until deflection continues without application of additional loads (e.g. plunging resistance). This definition is purely strength based and does not limit pile head deflection. Many structures are sensitive to movement and require limitations to total movement. The effective stiffness of the foundation also may be of interest. For this reason, the capacity of piles is often limited based on deflection.

Limiting pile capacity based on a minimum factor of safety relative to the ultimate capacity at failure and including a criterion for maximum tolerable total pile head movement at the design load satisfies the demands of most structures very well.

## REFERENCES

AC358 (2007) “Acceptance Criteria for Helical Foundation Systems and Devices”, ICC-Evaluation Services, Inc., Wittier, CA

ASTM D1143 “Standard Test Method for Piles Under Static Axial Compressive Load”, Annual Book of Standards, ASTM International

ASTM D3689 “Standard Test Method for Individual Piles Under Static Axial Tensile Load”, Annual Book of Standards, ASTM International

Brinch-Hansen, J. (1963) “Discussion on Hyperbolic Stress-Strain Response: Cohesive Soils”, Journal for Soil Mechanics and Foundation Engineering, Vol. 89, SM4, ASCE, pp. 241-242

Butler, H.D. and Hoy, H.E. (1977) "Users Manual for the Texas Quick-Load Method for Foundation Load Testing", Federal Highway Administration, Office of Development, Washington.

Cherry, J.A. (2012) "Deflection of Helical Piles: A Load Test Database Review", Slide Presentation, Helical Piles and Helical Tie-Backs Seminar, Deep Foundation Institute, Denver, CO

Cherry, J.A. and Souissi, M. (2010) "Helical Pile Capacity to Torque Ratios, Current Practice, and Reliability", GeoTrends: Proceedings of the 2010 Biennial Geotechnical Seminar, C.M. Gross, et al., Eds., ASCE, Denver, CO

Fellenius, B.H. (1980) "The Analysis of Results from Routine Pile Loading Tests", Ground Engineering, Foundation Publishing Ltd., Vol. 13, No. 6, pp. 19-31.

Fellenius, B.H. (1990) "Guidelines for the Interpretation and Analysis of the Static Loading Test", 1st Edition, Continuing Education Committee, Deep Foundation Institute, Sparta, NJ

Fellenius, B.H. (2001) “What Capacity Value to Choose from the Results of a Static Load Test”, Fulcrum, Winter, Deep Foundation Institute, pp. 19-22

Fleming, W.G.K., Weltman, A.J., Randolph, M.F., and Elson, W.K. (1985) Piling Engineering, Surrey University Press, Glasgow

IBC (2009) International Building Code, International Code Council

Perko, H.A. (2009) Helical Piles - A Practical Guide to Design and Installation, Wiley & Sons, New York