Shortcomings of the Davisson Offset Limit Applied to Axial Compressive Load Tests on Cast-In-Place Piles

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ABSTRACT

Since its introduction in 1973, the Davisson Offset Limit has been widely used in the United States for interpretation of axial compressive load tests on pile foundations and is one of three methods explicitly accepted by the 2006 International Building Code. An examination of the fundamental assumptions of the DOL shows that its application to cast-in-place piles lacks scientific basis and leads to over conservatism. Interestingly, these are the same reasons given by Davisson for its development. The results of the examination indicate that there are notable fallacies in the Davisson Offset Limit, including the assumptions that: (1) the cast-in-place pile behaves as a "fixed-base, free-standing column.", (2) an elastic line is a dependable reference line for interpretation of load tests on cast-in-place piles, and; (3) an offset of 3.8 mm + D (inches)/120 from the elastic line represents the movement necessary to mobilize toe resistance of cast-in-place piles. Considering these results, the authors present suggestions ranging from modifications to the Davison Offset Limit that recognizes the greater movement required to mobilize the toe resistance to codification of a more rational criterion better suited to interpret the axial compressive capacity of cast-in-place piles.

INTRODUCTION

The 2006 International Building Code explicitly accepts three interpretive methods for axial compressive load tests on piles. These three interpretative methods (by the names they are used in common vernacular): (1) Davisson Offset Limit (Davisson, 1972); (2) Brinch Hansen 90% Criterion (Brinch Hansen, 1963), and; (3) Butler-Hoy Criterion (Butler and Hoy, 1977). Generally speaking, the Davisson Offset Limit (DOL) is frequently used in the United States because it provides the lowest estimation of axial compressive capacity of the aforementioned methods. Also, it is most likely to provide an ultimate axial compressive pile capacity from the actual load-deflection curve. That is, the Brinch Hanson 90% Criterion and the Butler-Hoy Criterion often require extrapolation to extend the load-deflection curve in order to establish an ultimate axial compressive capacity. In the absence of established guidelines for extrapolation, there is a reluctance, and even opposition, to the extrapolation of load test results.

Its widespread application to all pile types in the US is sufficient justification for a critical examination of the appropriateness of the DOL, especially for the evaluation of load tests results for cast-in-place piles. The first part of this paper discusses the fundamentals that were involved in the formulation of the DOL and the fallacies associated with its application to load testing of cast-in-place piles. The second part of this paper presents examples of results from actual load tests that serve to illustrate the shortcomings of the DOL with respect to actual pile behavior and application to design. The third and final part of this paper presents suggestions for load test procedures and interpretation in light of the current understanding of geotechnical engineering.

FUNDAMENTALS OF THE DAVISSON OFFSET LIMIT

The Davisson Offset Limit (as it is currently referred to) was proposed by Davisson (1972) based on comparisons between the results of wave equation analyses of driven steel piles and static load tests. The DOL defined the ultimate pile load as the intersection of the pile load-deflection curve with an elastic line for a fixed-base, free-standing column offset by 3.8 mm (0.15 inches) plus the soil quake. Soil quake is the deformation (or pile movement) required to mobilize the strength of the soil below the pile tip. The soil quake is further simplified by the pile diameter (in inches) divided by 120. In his 1972 paper, Davisson is explicit that the criterion was developed for point bearing driven piles but goes on to state that it can also be applied to friction piles. Davisson explains his motivation in the paper's introduction:

> "There are many ways of interpreting a load test; almost all of them are unsatisfactory for high capacity piles. It appears that engineering practice is based primarily on experience, precedent, and perhaps prayer, even for low capacity piles. Because of the inadequate basis for practice, engineers tend toward over-conservatism in design; often this causes unnecessary problems. When the present day need for high capacity piles is considered in light of the state of practice with low capacity piles, it is obvious that engineers more than ever need a scientific basis for their engineering decisions."

FALLACIES OF THE DAVISSONS OFFSET LIMIT

Davisson was clearly aware of the challenges with load test interpretation and particularly, the tendency of the engineering community to accept over-conservatism in establishing the ultimate pile capacity. Ironically, the application (or misapplication) of the DOL to cast-in-place piles has not only led to greater conservatism but it fails as a rational, scientific criterion. The primary fallacies of the application of the DOL to cast-in-place piles are discussed in the following:

(1) **The assumption that the cast-in-place pile behaves as a "fixed-base, free-standing column."** Cast-in-place are generally designed using a combination of shaft and end resistances and the stress distribution in the pile element is unlike the "fixed-base, free-standing column" assumed by the DOL. This is especially true at test loads well below the ultimate capacity where the resistance is primarily developed along the shaft.

(2) **The assumption that an elastic line is a dependable reference line for interpretation of load tests on cast-in-place piles**. Kulhawy and Chen (2005) compared the estimated elastic shortening, based on the assumptions of the DOL, to the initial slope of the straight line portion of the load-deflection curve. Their study concluded that the DOL assumptions tended to overestimate the stiffness of short piles and underestimate the stiffness for longer piles.

(3) **The assumption that an offset of 3.8 mm + D (inches)/120 from the elastic line represents the movement necessary to mobilize toe resistance**. The soil quake proposed by Davisson is specifically for driven piles and is not appropriate where soil resistance beneath the pile toe has not been fully mobilized at the beginning of load testing. That is, Davisson study evaluated piles installed by driving where a compressed soil plug forms during placement. In contrast, cast-in-place piles and other types of drilled piles do not compress the soil beneath the pile toe during installation. Thus, a greater downward movement of the pile toe would be required to mobilize the end resistance for cast-in-place piles if all other conditions were equal. Analysis by Zheng *et al.* (2007) confirmed this based on results of load tests performed on displacement cast-in-place piles.

EXAMPLE LOAD TEST ANALYSES

Osceola, Arkansas Site

It is helpful to illustrate the shortcomings of the DOL using examples of actual load test results. For this purpose, we have selected test data from a load test performed by Berkel & Company Contractors, Inc. (Berkel) and published by Zheng *et al.* (2007). The data were collected during a quick load test (ASTM D1143) performed on a 457 mm (18 in) diameter displacement cast-in-place pile with a length of 12.8 m (42 ft). The load-deflection data are shown in Figure 1. Refer to the paper by Zheng *et al.* (2007) for details concerning the geotechnical conditions at the test site.

The DOL is illustrated by two lines in Figure 1. In this case, the elastic line was intentionally fit to the initial straight line portion of the load-deflection curve and corresponds to a slope of 37,200 MPa (5.4 x 10^6 psi). Intuitively, if the fundamental assumptions of the DOL are valid, then the combined modulus (*i.e.*, both grout and reinforcing steel) should closely correspond to the slope of the initial straight line portion of the load-deflection curve. In fact, strain gage measurements obtained in the upper portion of the cast-in-place pile indicate a combined modulus ranging from about 27,500 to 34,500 MPa (4 to 5 x 10^6 psi) which is significantly smaller than the slope of the straight line portion. This shows that not only does the DOL fail to appropriately represent a pile with substantial shaft resistance, but also suggests that selection of the appropriate modulus becomes problematic due to the stress-dependant non-linearity of the pile materials.

The DOL line was constructed by offsetting the elastic line by a distance of 3.8 mm (0.15 inches) plus the pile diameter in inches divided by 120. According to the DOL, the axial compressive capacity of the pile is 2200 kN (450 kips). However, it is clear that the pile is capable of resisting additional compressive load up to 2850 kN (640 kips) at which point the test load was removed. It is recognized that Davisson (1993) proposed that the pile width (and thus the soil quake term) be multiplied by a factor of 2 to 6 for drilled piles in recognition of the greater pile movement that is required to mobilize the toe resistance. However, such a modification has yet to be formally established in those codes that specify the DOL, and as a result, incorporation of such a modification has not been widespread in engineering practice. Also, the different modifier values results in a wide range of pile capacity interpretations.

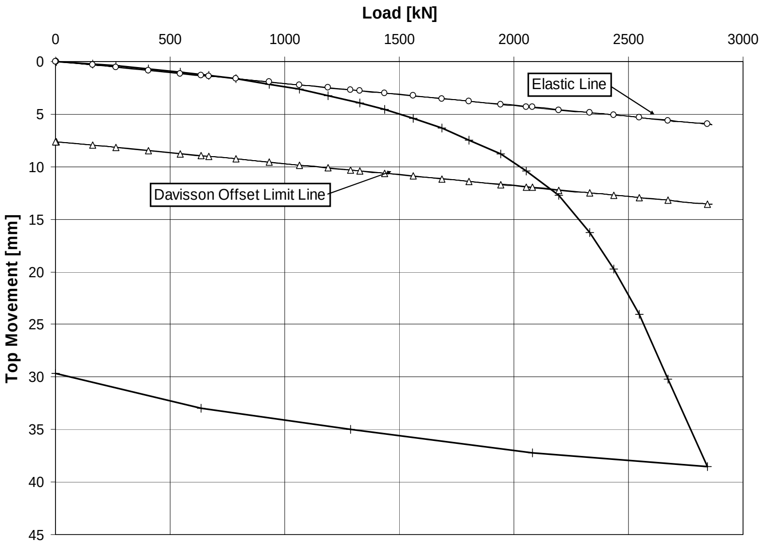

FIG 1. Load Versus Top Deflection Curve – Osceola AR Site (after Zheng *et al.*, 2007)

Des Moines, Iowa Site

A second example is from a load test performed by Berkel in Des Moines IA. The data were collected during a quick load test (ASTM D1143) performed on a 457 mm (18 in) diameter displacement pile with a length of 12.8 m (34.5 ft). The subsurface conditions at the pile location are characterized by a stiff fine-grained soil to about 6.1 m (20 ft) depth underlain by loose to dense clean sands. The load-deflection data are shown in Figure 2 along with a summary of ultimate load analysis methods. The methods include the three specifically listed in IBC 2006 as well as a method proposed by NeSmith (2002). This method was developed from a database of drilled, cast-in-place piles, and is based on defining ultimate load such that, applying a factor-of-safety of 2, the pile head deflection at the allowable load is no more than 6.4 mm (0.25 in).

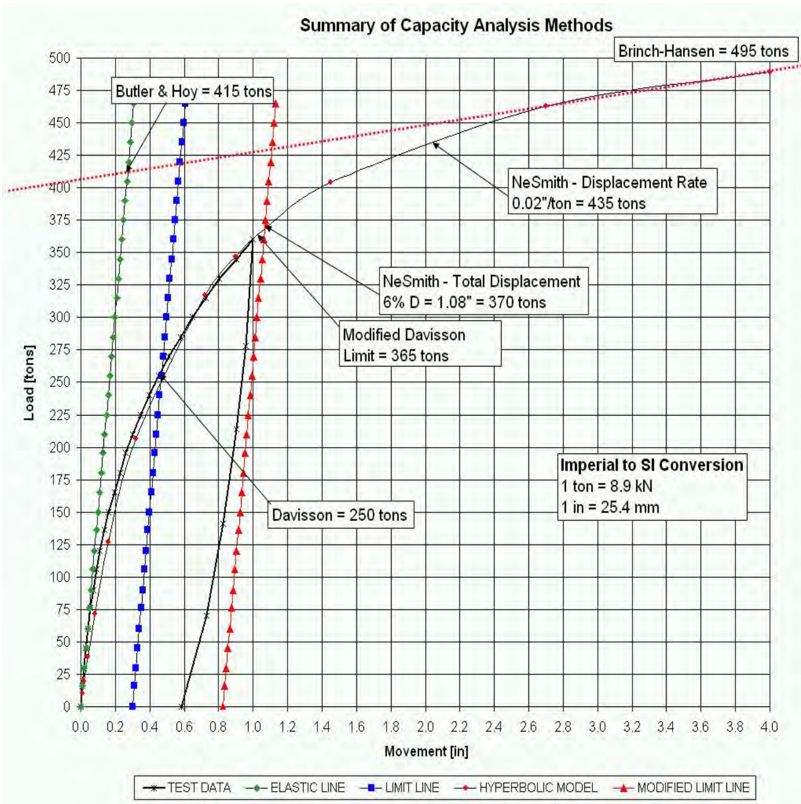

FIG 2. Applied Load vs. Pile Head Deflection and Ultimate Load Analysis

Again, it is clear that the pile is capable of resisting additional compressive load beyond the ultimate load defined by the DOL. For this project, a modifier of 4.5 was applied to the soil quake term in the DOL equation to obtain an ultimate load value in the range of the most conservative of the other three methods shown. A review of recent load tests available to the authors (performed from January 2007 to August 2008) indicates that offset modifiers of between 4 and 5 are typically required to obtain ultimate load values from the DOL that are in the range of those as calculated by the NeSmith (2002) method.

DISCUSSION AND SUGGESTIONS

An examination of the fundamental assumptions of the DOL shows that its application to cast-in-place piles lacks scientific basis and leads to over conservatism. Interestingly, these are the same reasons given by Davisson for its introduction in 1973. Because of its ease in application rather than its technical merit, the DOL continues to be widely used in the United States for the interpretation of load tests performed on all pile types. Due to its conservatism and, arguably, over-conservatism, the use of the DOL dramatically increases the likelihood of greater foundation costs.

The authors' experience is that the DOL is often applied indiscriminately with an end result of greater foundation costs unnecessarily. In light of this, the following suggestions are offered for the load test procedure and interpretation of cast-in-place piles:

- Ideally, load tests should be carried to a top deflection that allows the application of the Brinch Hanson 90% Criterion, Butler-Hoy Criterion, and/or other methods appropriate for cast-in-place piles. It is noted that most recent version of ASTM D1143 (2007) lists the Quick Load method as the standard compressive load test method with load to be applied in increments of about 5% of the estimated failure load and continuing until geotechnical failure.

- When the load tests are not carried to definitive geotechnical failure, the authors recommend the rational (and limited) extrapolation of the load-deflection curve to allow the application of either the Brinch Hanson 90% Criterion or the Butler-Hoy Criterion. A review of the load test data available to the authors indicates that at pile-head deflections of about 5% of the pile diameter, sufficient mobilization of the pile toe has occurred to allow for reasonable extrapolation according to the method described by Chin (1970)

- In the long term, a more rational criterion for establishing the cast-in-place pile capacity should be codified. Most notably, the L_1-L_2 method proposed by Hirany and Kulhawy (1989) recognizes aspects specific to cast-in-place piles. Furthermore, Kulhawy and Chen (2005) have combined the L_1-L_2 method with the slope tangent method to allow an empirical projection of axial compressive pile capacity.

- As a minimum (assuming none of the aforementioned changes have been implemented), the soil quake component should be modified as proposed by Davisson (1993) for cast-in-place piles when establishing the offset line for the DOL.

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