APPLYING SEPARATE SAFETY FACTORS TO END-OF-DRIVE AND SET-UP COMPONENTS OF DRIVEN PILE CAPACITY

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ABSTRACT: A driven pile's long-term capacity is often the sum of two components: end-of-initial-drive capacity, and set-up (time-dependent capacity increase). Incorporating set-up into pile design and installation procedures has many economic advantages (potentially millions of dollars), and is increasing in acceptance and application among designers. For a number of reasons, it may be desirable to apply separate (different) safety factors to the end-of-initial-drive capacity and set-up components. This approach is particularly well-suited to load and resistance factor design, which is anticipated to be used on all new bridge designs after 2007. The analytical approach to applying separate factors of safety is presented, and its application is illustrated in a case history from the Marquette Interchange project in Milwaukee, Wisconsin. In the case history, separate safety factors for end-of-initial-drive capacity and set-up were selected based on the results of a design-phase pile test program, and set-up safety factors varied with pile diameter.

INTRODUCTION

The use of load-factor design procedures is not new to the structural community, their use for bridge superstructure design is expanding rapidly. However, portions

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of substructure design (e.g., geotechnical pile capacity) is traditionally based on allowable stress methods. Applying separate safety factors to account for differing uncertainties among pile design components has received increased interest in recent years. This method shares many principles with the Load and Resistance Factor Design ("LRFD") approach.

A pile under load can fail for lack of structural capacity, or for lack of geotechnical capacity (by unacceptable penetration into the ground). Structural failures of piles meeting the specified installation criteria are rare, and are not further discussed. A driven pile's long-term geotechnical capacity is often the sum of two separate and distinct components: its end-of-initial-drive ("EOID") capacity, and set-up. This paper deals with these two components of geotechnical capacity.

The methods used to estimate EOID capacity and set-up may differ. Capacity analysis methods may differ by component (EOID capacity vs. set-up), and by when they are performed (during design vs. during construction). The results of such analyses may have different degrees of uncertainties, or may yield different ranges of results. As part of the overall design process, it is important that the foundation designer qualitatively assess the reliability of the geotechnical design parameters. For these reasons, it may be desirable to apply separate safety factors to EOID capacity and set-up.

This paper describes some of the methods available to evaluate EOID capacity and set-up (during both design and construction), and potential reasons for applying separate safety factors to these two capacity components. An analytical approach is presented for application of different safety factors to EOID capacity and set-up. A case history is presented which describes the analytical approach, discusses the role design-phase test results played in the selection of separate safety factors, and illustrates the application in developing installation criteria.

SOIL/PILE SET-UP

It is known that after installation, pile capacity may increase with time. This capacity increase is known as set-up, and was first mentioned in the literature in 1900 by Wendel [Long et al., 1999]. Set-up has been documented in fine-grained soils in most parts of the world [Soderburg, 1961], and has been demonstrated to account for capacity increases of up to 12 times the initial value [Titi and Wathugala, 1999]. Set-up rate and magnitude is a function of a combination of a number of factors [Komurka et al., 2003a; Samson and Authier, 1986], the interrelationship of which is not well understood. Set-up is primarily attributable to an increase in shaft resistance [Axelsson, 2002; Bullock, 1999; Chow et al., 1998].

Incorporating set-up into pile design and installation has many advantages, and is increasing in acceptance and application among designers and agencies. By incorporating set-up into design, it may be possible to increase allowable pile loads, and to reduce: the number of piles, pile lengths (and potentially splices), pile sections (use smaller-diameter or thinner-walled pipe piles, or smaller-section H-piles), driving equipment size (use smaller hammers and/or cranes), or installation time, all of which should result in lower costs. A number of projects have documented savings in the millions of dollars.

POTENTIAL REASONS TO APPLY SEPARATE SAFETY FACTORS

Pile capacity must exceed applied loads by a sufficient margin so that the foundation does not fail structurally or geotechnically. Safety factors are applied to pile capacities (resulting in allowable loads) to account for uncertainties in applied load (loads or loading conditions, load determination methods, foundation stiffness, thermal effects, etc.) and uncertainties in resistance to those loads (extent and quality of the site investigation program including field and laboratory testing, variability of subsurface conditions across the site, reliability of soil strength data, pile capacity evaluation methods, quality control procedures (including the ability to install the pile without structural defects and capacity verification measures), pile material properties, installation equipment performance, environmental effects, etc.).

Discussion of specific safety factor selection based on these factors is beyond the scope of this paper. Statistical methods can assess risk, and form the basis for the safety factors proposed by modern codes. Likins (2004) presents a review of several codes' recommended safety factors, showing most codes relate safety factor selection to the type and amount of capacity verification performed.

To estimate set-up, pile capacity requires evaluation, both at EOID and at some later time. There are a number of approaches to evaluating capacity at EOID and at some later time, each with its own associated limitations and uncertainties. For this, and other, reasons, it may be desirable to apply separate safety factors to these two capacity components.

Capacity Components' Evaluation Methods

The capacity determination methods used to evaluate EOID and longer-term capacity may have different associated uncertainties. For example, design-phase EOID capacity may use dynamic testing and CAse Pile Wave Analysis Program (CAPWAP®) analyses. Longer-term capacities (set-up) may be estimated using empirical formula, or extrapolated from relatively short-term static loading or restrike tests. In this case, EOID capacities may be considered to have less uncertainty than set-up. An awareness of relative uncertainties between EOID capacity and set-up evaluations should play a role in the decision to use, and the selection of, separate safety factors.

Design-Phase — End-Of-Initial-Drive Capacity Determination

<u>Static Analysis</u> — Static analysis methods can be categorized as analytical methods which use soil strength/relative density properties to determine pile capacity, and so do not rely on any pile driving data. A large number of static analysis methods are documented in the literature, with specific recommendations on the safety factor to be used with each method (although these recommended safety factors have routinely discarded the influence of the construction control method used to complement the static analysis computation). Most static analysis methods recommend a safety factor of 3. Piles whose designs are based solely on static analyses (albeit rare) might be installed to a minimum depth criterion. In comparison with the other methods described (with the possible exception of certain dynamic formulas), static analyses are typically considered to have the greatest degree of uncertainty.

Dynamic Formulas — Dynamic formulas are based on energy concepts relating energy applied by the hammer to work done by the pile penetrating the soil, and so rely on penetration resistance (pile set per blow) during driving to analyze capacity. The inadequacies of dynamic formulas have been known for a long time [Peck, 1942]. Dynamic formulas are fundamentally incorrect: the derivation of most formulas is not based on a realistic treatment of the driving system, the soil resistance is very crudely treated by assuming it is a constant force, and usually the pile is assumed to be rigid and its length is not considered. Regarding the actual safety factor obtained by using the Engineering News formula (a popular dynamic formula), Chellis (1961) noted that it ranged from 1/2 to 16, Sowers (1979) reported that it ranged from 2/3 to 20, and Rausche et al. (1996a) determined that it ranged from 0.6 to 13.1. While most formulas are typically considered to have less uncertainty than static analysis methods, dynamic formulas are considered to have relatively high uncertainties when compared to wave equation analysis and dynamic pile testing and analysis.

Wave Equation Analysis — Wave equation analysis offers a complete approach to the mathematical representation of a system consisting of hammer, cushion(s), helmet, pile, and soil, using an associated computer program for the convenient calculation of the motions and forces in this system after ram impact. The approach was developed by E.A.L. Smith (1960). After the rationality of the approach had been recognized, several researchers developed a number of computer programs. Although wave equation analysis can be used to evaluate a number of installation parameters (e.g., driving stresses), a primary application is to develop a bearing graph relating pile capacity to penetration resistance. Relatively speaking, this method has less uncertainty than either static analysis or most dynamic formulas. However, this method lacks direct measurement on a driven pile at the project site, and therefore is considered to have more uncertainty than dynamic pile testing and analysis.

Dynamic Pile Testing and Analysis — Dynamic pile testing methods use measurements of strain and acceleration taken near the pile head as a pile is driven. Among other things, these dynamic measurements can be used to estimate static pile capacity in the field during driving using the Case Method [Goble and Rausche, 1970; Goble et al., 1975; Rausche et. al., 1985]. Subsequent additional analysis of dynamic monitoring data may include performing a CAPWAP analysis (a rigorous numerical modeling technique) to refine capacity estimates, and to provide assessment of capacity allocation (toe resistance versus shaft resistance, and shaft resistance distribution) [Hussein et al., 2002; Likins et al., 1996; Likins and Rausch, 2004; Rausche et al., 1972, 1994, 1996b, 2000]. Since this method involves direct measurements on a driven pile at the project site, it is generally considered to have the least degree of uncertainty of the methods described.

Design-Phase — Set-Up Determination

To determine set-up, pile capacity must be evaluated at EOID and at some later time. EOID capacity is subtracted from longer-term capacity to determine set-up. Since set-up is the difference between EOID capacity and longer-term capacity, the accuracy of set-up so determined is sensitive to the accuracy of both EOID, and longer-term, capacity evaluations [Komurka, 2004]. Accordingly, set-up has greater uncertainty than either EOID or longer-term capacity.

Static Analysis — Some static analysis methods may have provision for incorporating set-up. Such provision may be in the form of inputting a set-up factor, a cohesive soil sensitivity, or a percentage strength loss during driving. These inputs, and the reliability of the method, may be based on soil type, field or laboratory testing results, published relationships, local experience, etc. If a static analysis method is empirically correlated to static loading test results, set-up may already be incorporated into the correlation since a static loading test cannot be performed instantaneously after driving (i.e., set-up occurs before the static loading test can be performed). Designers should fully understand the basis for, and the limitations and applicability of, a chosen static analysis method, particularly with respect to incorporating set-up into design. Even with such an understanding, such set-up evaluations are typically considered to have a high degree of uncertainty.

Empirical Relationships — A number of researchers have offered empirical relationships for predicting pile capacity with time if capacity at some initial time is known [Guang-Yu, 1988; Huang, 1988; Skov and Denver (1988); Svinkin, 1996; and Svinkin and Skov (2000)]. Such relationships are subject to a number of limitations (Komurka et al., 2003b), and should be used judiciously by designers with local experience correlating predictions to results. The relative uncertainty of empirical relationships' set-up predictions depends on how closely the project conditions emulate the conditions and assumptions on which the relationships were based.

Restrike Testing — Restrike testing involves redriving a pile with a pile driving hammer some time after installation to evaluate longer-term capacity. For dynamic formula and wave equation analysis, restrike testing penetration resistance is used to evaluate capacity. For Case Method estimates and CAPWAP analyses, dynamic measurements obtained during restrike testing are used to evaluate capacity. Because of set-up, mobilizing full capacity during restrike testing often requires a larger hammer (i.e., more impact force) than used for installation. Since restrike testing involves direct measurements on a driven pile at the project site, it can have a relatively low uncertainty, but its associated uncertainty depends on if full capacity is mobilized, type of restrike data obtained, and the method of analysis applied to the data.

Static Load Testing — Static loading tests have traditionally been the standard for evaluating pile capacity. If set-up is present, the capacity measured by a static loading test almost always includes a set-up component, since a static loading test cannot be performed instantaneously after driving. To evaluate set-up from a static loading test, EOID capacity must be subtracted from the static-loading-test-determined capacity (determining set-up distribution from a static loading test requires instrumentation to evaluate load transfer behavior). Accordingly, the relative uncertainty associated with set-up determination from a static loading test lies predominately with the EOID capacity evaluation.

Construction Phase — EOID Capacity and Set-Up Determination

Many of the same capacity determination methods used in the design phase can also be employed in the construction phase. However, uncertainties associated with each of these methods may differ from their use in the design phase, due to construction control procedures. For example, construction control procedures may include periodic EOID capacity evaluation using dynamic testing and CAPWAP analyses, with provision to modify installation criteria based on results. Longer-term capacities (set-up) may not be evaluated further during construction, or may be evaluated with relatively short-term restrike testing and extrapolated to longer-term capacity. In this case, EOID capacities may be considered to have less uncertainty than set-up.

Site Coverage

EOID capacity and set-up evaluation uncertainties may depend on the extent to which testing can characterize a site. For example, in a relatively small building footprint, a design-phase test program may characterize driving behavior and set-up to a greater extent than possible on a project of large plan area (e.g., an interchange). If relatively less testing coverage means more interpolation or extrapolation of results is required for design, and EOID capacity variations are accounted for by penetration resistance criteria, EOID capacities may be considered to have less uncertainty than set-up.

Variability of Results

Test results may indicate variable pile behavior (both EOID capacity and set-up), even between relatively proximate locations, or between apparently similar soil conditions. With penetration-resistance-based installation criteria, variations in EOID capacity are evidenced and accounted for during installation by variations in penetration resistance. Potential variations in set-up are much less discernable during driving. In this case, EOID capacities may be considered to have less uncertainty than set-up.

Application of Results

Test results may be applied to slightly different piles than from which the results were obtained (e.g., applying unit shaft resistance or unit set-up values obtained from 12.75-inch-diameter test piles to 14-inch-diameter production piles). Increased uncertainties in both EOID capacity and set-up are likely with such extrapolation.

Relative Contribution of Set-Up to Pile Capacity

The effort of deciding to use, selecting, and applying separate safety factors for EOID capacity and set-up may not be worthwhile if anticipated set-up provides a relatively small contribution to pile capacity. In this case, actual set-up significantly less than anticipated in design may result in a relatively minor reduction in the overall safety factor. Conversely, if anticipated set-up provides a relatively large contribution to pile capacity, actual set-up significantly less than anticipated in design may result in an unacceptable reduction in the overall safety factor. In this case, consideration should be given to applying a higher safety factor to set-up.

Compatibility With Load and Resistance Factor Design

It may be possible to incorporate applying separate safety factors to EOID capacity and set-up of driven piles into the Load and Resistance Factor Design ("LRFD") method, or other load-factor methods. Mechanisms for applying resistance factors to geotechnical pile capacities in LRFD have been documented by Liang and Nawari (2000), and Paikowsky (2004). Additional discussion of LRFD and/or other load-factor methods in the design and installation of deep foundations have been presented by Goble, et al. (1980), Likins (2004), and Long (2002). However, application of the LRFD concept to foundation design is not universally accepted, and doubts have been expressed about its use [Svinkin, 2003].

Acceptance of Set-Up in Design

A pile foundation designer's recommendation to incorporate set-up into driven pile design and installation may be received with reluctance or skepticism from others (an owner, a reviewing agency, design team members, etc.). For these others involved, it may be a first-time use or a relatively new approach, or set-up magnitudes or relative contributions may be high enough to foster reservations. In such cases, an appropriately high set-up safety factor may increase comfort levels so that incorporating set-up into design is acceptable. Incorporating set-up with a high safety factor is better than ignoring set-up completely.

INCORPORATING SEPARATE SAFETY FACTORS INTO PILE DESIGN

Overall Safety Factor

The uncertainties discussed in the previous section can be addressed using a load-factor procedure. This procedure shares the same philosophy as LRFD, in that the EOID and set-up components of long-term capacity are assigned separate safety factors respective of their relative uncertainty.

The relative contributions from EOID capacity and set-up to ultimate long-term capacity influence the affect of each component's uncertainties on the overall safety factor[4]. The overall safety factor can be determined starting with:

$$EOID + SetUp = ULTC \qquad (1)$$

where:
EOID = EOID Capacity Component of Ultimate Long-Term Capacity
SetUp = Set-Up Component of Ultimate Long-Term Capacity
ULTC = Ultimate Long-Term Capacity

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[4] "Ultimate capacity" is a misnomer, as capacity of the deep-foundation element (e.g., "bearing capacity," "uplift capacity," "shaft capacity," and "toe capacity") is the ultimate resistance of the element. It cannot be misunderstood, however, and aids avoiding confusion with allowable load, and so is used herein.

Dividing by respective safety factors yields:

$$\frac{EOID}{SF_{EOID}}+\frac{SetUp}{SF_{SETUP}}=\frac{ULTC}{SF_{OVERALL}}=Allowable\quad Load \tag{2}$$

where: SF_{EOID} = Safety Factor Applied to EOID Component of Ultimate Long-Term Capacity
SF_{SETUP} = Safety Factor Applied to Set-Up Component of Ultimate Long-Term Capacity
$SF_{OVERALL}$ = Overall Safety Factor
Allowable Load = Allowable Pile Load

Cross-multiplying to determine a common denominator, and rearranging, yields:

$$SF_{OVERALL}=\frac{ULTC\times SF_{EOID}\times SF_{SETUP}}{EOID\times SF_{SETUP}+SetUp\times SF_{EOID}} \tag{3}$$

Inspection of Eq. 3 indicates that as a capacity component's relative contribution increases, the overall safety factor approaches that component's safety factor.

As discussed previously, uncertainty associated with a capacity component which has a relatively small contribution to long-term capacity has diminished effect on the overall safety factor. Consider two cases: the first in which set-up is anticipated to contribute relatively little (on the order of ten percent) to long-term capacity, and the second in which set-up is anticipated to contribute significantly (on the order of 70 percent) to long-term capacity. If only half the anticipated set-up actually occurred, the resulting actual overall safety factor would be affected much less for the first case than for the second case. Accordingly, consideration could be given to applying a lower set-up safety factor for the first case than for the second case.

Required End-Of-Initial-Drive Capacity

For installation criteria development, after a desired allowable load is selected, the EOID capacity to which the piles should be installed is of principal interest. Multiplying both sides of Eq. 2 by SF_{EOID} results in:

$$Req'd\quad EOID+SetUp\times\frac{SF_{EOID}}{SF_{SETUP}}=Desired\quad Allowable\quad Load\times SF_{EOID} \tag{4}$$

The term {SetUp x (SF_{EOID} / SF_{SETUP})} in Eq. 4 is herein referred to as the "adjusted set-up." It should be noted that both sides of Eq. 2 could just as easily have been multiplied by SF_{SETUP}, in which case required EOID capacity would be adjusted, and allowable load would have been multiplied by SF_{SETUP}. It should also be noted that a pile's overall safety factor is not the factor by which the allowable pile load is multiplied in Equation 4, but instead is determined by Eq. 3. The sum of EOID capacity plus unadjusted (actual) set-up still equals the ultimate long-term capacity. Rearranging Eq. 4 results in:

$$Req'd\ \ EOID = (Desired\ \ Allowable\ \ Load) \times SF_{EOID} - SetUp \times \frac{SF_{EOID}}{SF_{SETUP}} \quad (5)$$

With Eq. 5, required EOID capacity can be determined using the set-up magnitude used for design, the desired allowable pile load, and separate safety factors for EOID capacity and set-up. This methodology is demonstrated in the following case history example.

The quantity {(Desired Allowable Load) x SF_{EOID}} in Eq. 5 is merely a value from which adjusted set-up is subtracted to determine required EOID capacity. It should not be confused with the ultimate long-term capacity in Eq. 1. This distinction is illustrated in the case history.

CASE HISTORY EXAMPLE

Project Description

The Marquette Interchange project at the junction of interstate highways I-43 and I-94 near downtown Milwaukee, Wisconsin, is an $810-million interchange replacement project, is the largest in state history, and is currently the most-complex design underway in the country. Encompassing 80 acres, the project includes two million square feet of bridge decks, 19 bridge structures, supported by 265 substructures, and is classified by the Federal Highway Administration as a megaproject.

In the summer of 2003, a $2-million design-phase pile test program was performed, with emphasis on characterizing EOID capacity, set-up, and long-term capacity as functions of depth for use in design, installation, and production control of driven pile foundations. Eighty-nine test piles, consisting of 12.75-, 14-, and 16-inch-diameter closed-end steel pipe, were driven. A detailed description of the test program is beyond the scope of this paper. To characterize set-up, dynamic monitoring using a Pile Driving Analyzer® ("PDA") [Goble et al., 1975; Hannigan et al., 1997; Pile Dynamics, Inc., 1998; Rausche et al., 1985] was performed during installation, and during subsequent restrike testing. CAPWAP analyses were performed on dynamic monitoring data from representative EOID and beginning-of-restrike ("BOR") blows.

Separate Safety Factors

Design-phase pile test program results were reviewed to select appropriate separate EOID capacity and set-up safety factors. At review time, it was desired to provide the design option of using 12.75-, 14-, or 16-inch-diameter steel pipe piles of various wall thicknesses, with allowable loads of up to 150, 200, and 250 tons, respectively.

For EOID capacity predictions, two Case Method equations, RA2 and RX9, were used to evaluate capacity vs. penetration depth during installation. The RA2 and RX9 capacities were compared to one another, and also to CAPWAP results.

For set-up prediction, unit set-up distributions (discussed subsequently) among piles were compared. This comparison indicated that unit set-up distributions varied, sometimes significantly, among relatively proximate piles. The effect of this variation (and potential overprediction of set-up) on reducing the actual overall safety factor was evaluated for a number of potential design cases. Detailed discussion of this evaluation is beyond the scope of this paper. It was determined that the extent to which the actual overall safety factor is reduced by potential overprediction of set-up is a function of the desired overall safety factor, allowable pile load, pile diameter, and set-up's relative contribution to long-term capacity.

The separate safety factors adopted by the design team and Owner as a result of this evaluation are presented in Table 1.

TABLE 1. Safety Factors Used for Design and Installation.

Pile Diameter, inches	Capacity Component	
	EOID	Set-Up
12.75	2.25	2.50
14	2.25	2.50
16	2.25	2.75

Set-Up Used for Design

For this project, CAPWAP results were used to estimate unit shaft resistance distribution (unit shaft resistance as a function of depth) at EOID and at BOR. For each pile, the EOID unit shaft resistance distribution was subtracted from the BOR unit shaft resistance distribution to yield a unit set-up distribution (unit set-up as a function of depth) for the pile's full length. This determination for one of the 12.75-inch-diameter test piles (Test Pile IPS-12-12) is presented in Figures 1a through 1c.

Cumulative set-up as a function of pile toe depth/elevation was determined for each pile by applying the unit set-up distribution to the surface area of the pile, and cumulatively summing set-up magnitude versus depth. These test program unit shaft resistance and cumulative set-up results are ultimate values. Ultimate cumulative set-up for IPS-12-12 is presented in Figure 2. Komurka (2004) details this approach to characterizing set-up.

Required End-Of-Initial-Drive Capacity

For this example, the desired allowable load is 150 tons. Substituting into Eq. 4 yields:

The relationships presented by Eqs. 1 and 6 are illustrated in Figure 2. The sum of

$$Req'd \quad EOID + SetUp \times \frac{2.25}{2.50} = 150 \quad tons \times 2.25 = 337.5 \quad tons \tag{6}$$

EOID capacity plus unadjusted (actual) cumulative set-up equals the ultimate long-term capacity (which in this example is equal to or greater than 337.5 tons). At any pile toe depth/elevation, the required EOID capacity plus the adjusted cumulative set-up equals 337.5 tons.

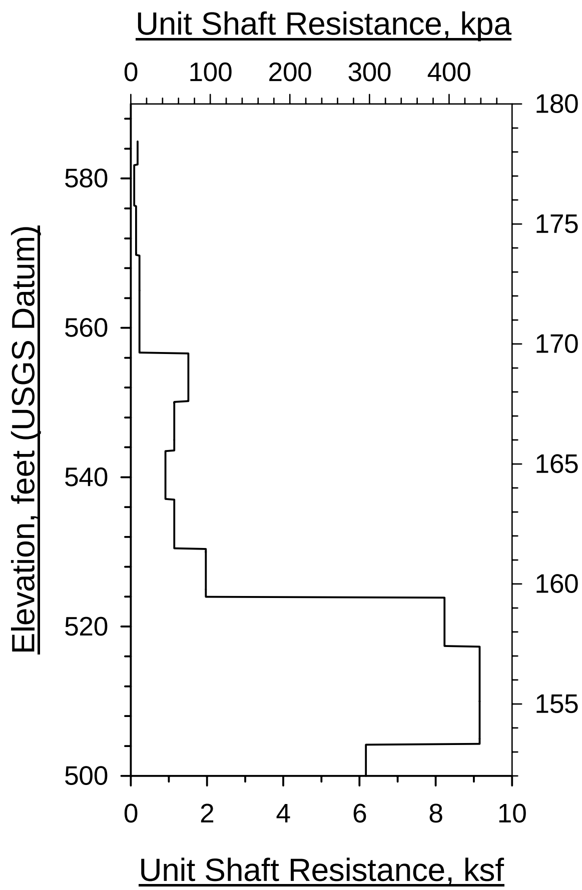

Fig. 1a. BOR CAPWAP Unit Shaft Resistance vs. Elevation.

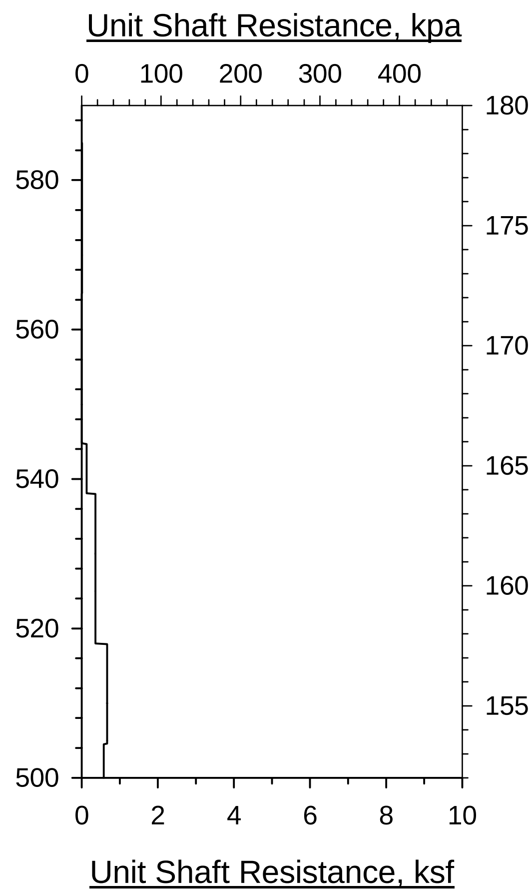

Fig. 1b. EOID CAPWAP Unit Shaft Resistance vs. Elevation.

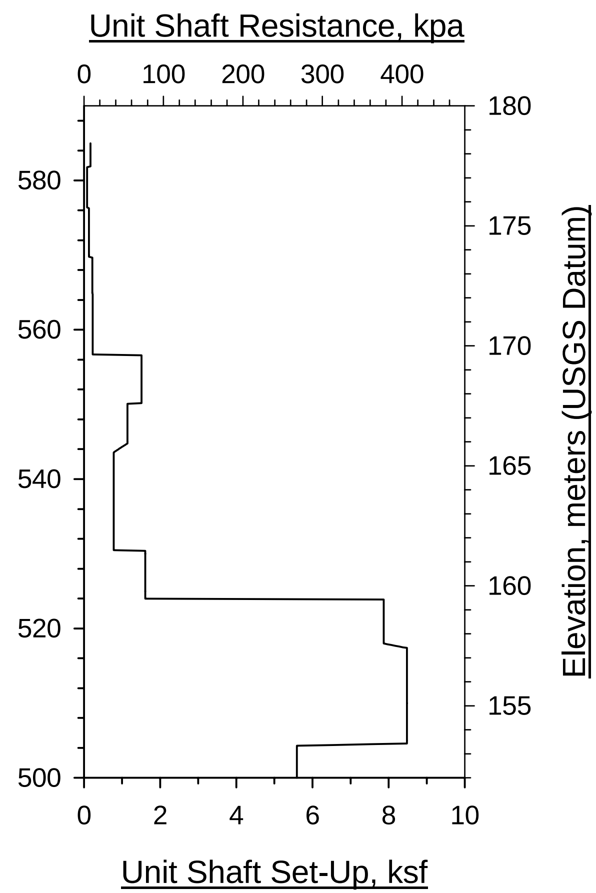

Fig 1c. EOID/BOR CAPWAP Unit Set-Up vs. Elevation.

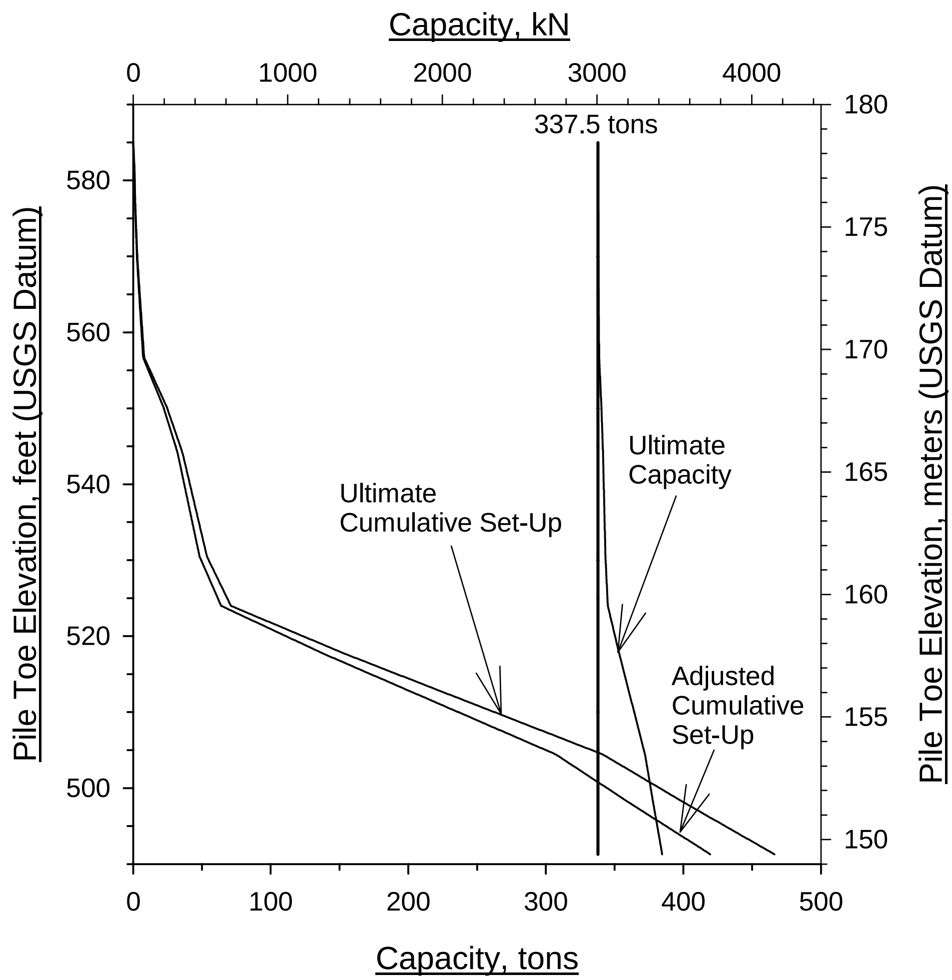

Fig 2. Capacity vs. Pile Toe Elevation.

Rearranging Eq. 6 yields:

$$Req'd \quad EOID = 337.5 \quad tons - SetUp \times \frac{2.25}{2.50} \tag{7}$$

The relationship presented by Eq. 7 for required EOID capacity for a given pile toe elevation is illustrated in Figure 3.

For example, in Figure 3 at pile toe Elevation 513, adjusted cumulative set-up equals 198 tons, requiring 139.5 tons EOID capacity. A review of Figure 3 indicates that since cumulative adjusted set-up increases with pile toe depth, required EOID capacity decreases with depth. This required EOID capacity decrease with depth, from which depth-variable installation criteria can be determined, is illustrated in Figure 4. Depth-variable installation criteria, which account for cumulative set-up increasing with depth in this way, were discussed in Komurka (2004).

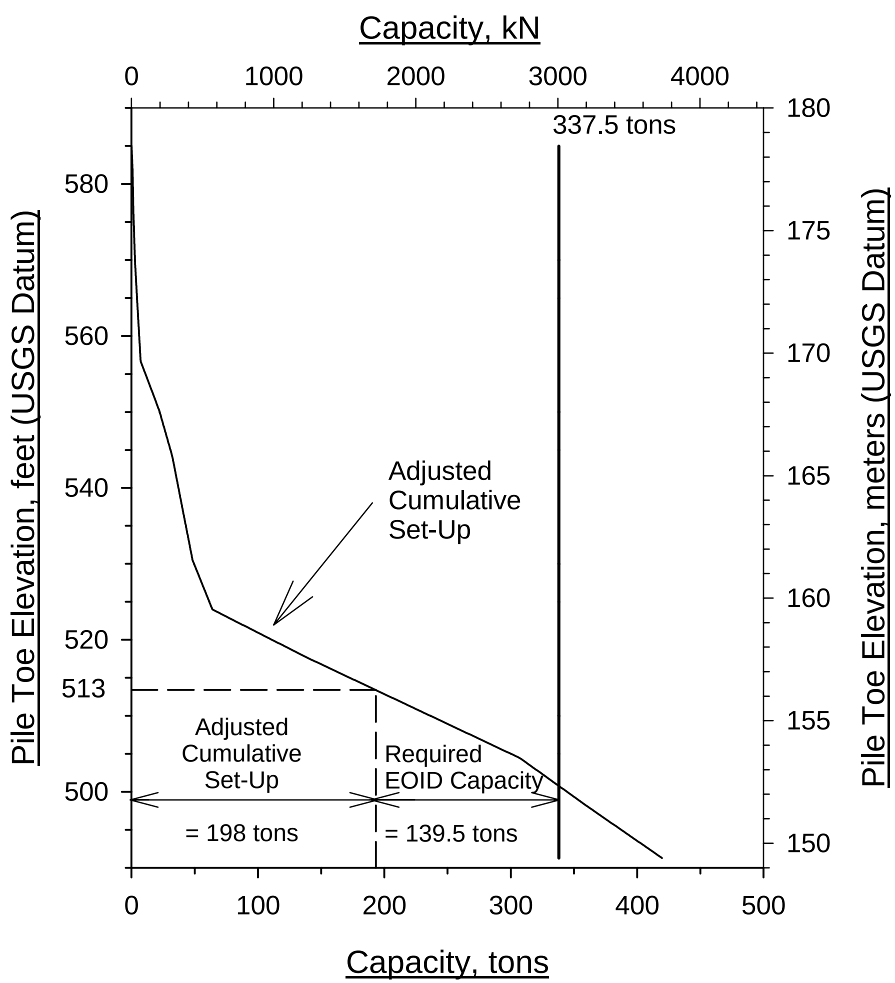

Fig 3. Capacity vs. Pile Toe Elevation.

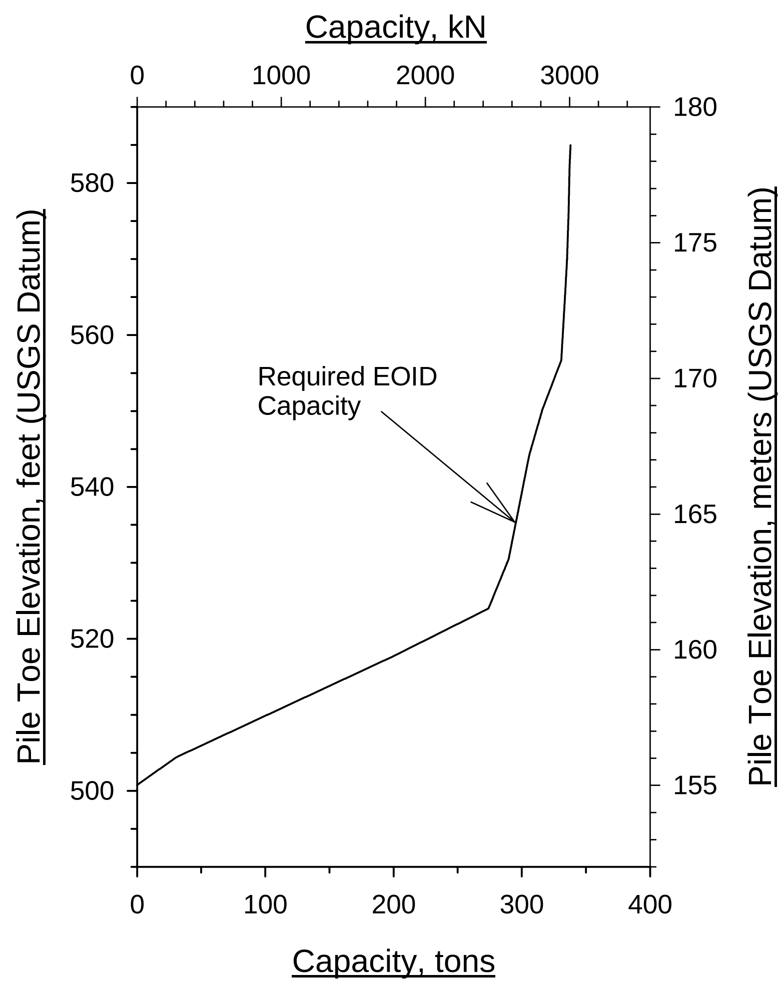

Fig 4. Required EOID Capacity vs. Pile Toe Elevation.

CONCLUSIONS

A driven pile's long-term capacity is often the sum of two components: EOID capacity and set-up. A number of methods may be used to estimate these two capacity components, whether during design or during production driving (i.e., construction control), and the methods may have different degrees of uncertainty. For this reason, and number of others, it may be desirable to apply separate and different safety factors to EOID capacity and set-up.

Safety factor selection may depend on a number of factors, and a number of codes contain selection provisions. Once separate safety factors for EOID capacity and set-up are selected, and a desired allowable load is established, the required EOID capacity to which the piles should be installed can be determined.

APPENDIX I. CONVERSION TO SI UNITS

1 foot (ft) = 0.3048 meters (m)
1 kip per square foot (ksf) = 47.88 kilopascals (kPa)
1 U.S. ton = 8.896 kilonewtons (kN)

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KEY WORDS

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