PILE TESTING – SELECTION AND ECONOMY OF SAFETY FACTORS

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ABSTRACT: Historically, while driven piles were designed conservatively by a static analysis, and then almost always installed to a driving formula, the inaccuracy of dynamic formulae for field verification of pile capacity is widely recognized. In some cases the design was verified by a static load test, performed along ASTM D1143 (1994) procedures to a maintained load of two times the design load, which engineers viewed as having the same effect as the pile having a safety factor of two. However, since static tests rarely failed, the actual safety factor was certainly higher.

Modern piling practices have seen several improvements. The Federal Highway Administration (FHWA) actively promoted quick static loading procedures to up to three times the design load. Computer analyses with the so-called "wave equation" (with realistic models for hammer, pile, and soil) have largely replaced dynamic formulae. Over the last 30 years, dynamic pile testing has become routine due to (a) good correlation with static tests to failure, (b) the additional information it provides on hammer performance and driving stresses, and (c) the economy of this testing.

Codes, both in public and private sectors, have been developed for both load and resistance factor design (LRFD) and allowable stress design (ASD) to minimize the risk of foundation failures. The selection of global safety factors (or LRFD resistance factors) to satisfy a foundation design with tolerable risk and at an acceptable cost relates to the type and amount of capacity verification performed. Based on a review of several codes, a comparison of traditional methods of dynamic formulae and static analyses with modern methods of analysis and testing is made, demonstrating the economics of the modern methods through the reduction in safety factors.

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INTRODUCTION

When designing a foundation system, engineers have many choices, including the ultimate load per pile and pile size (type, length, and diameter). The ultimate pile capacity must exceed the applied loads by a sufficient margin or the foundation will have unacceptable movements, or even fail. The required pile capacity also depends on the test method for verification of the pile capacity, and the frequency of testing. Additional geotechnical considerations like consolidation in compressible layers, changes in effective stresses due to changes in the groundwater table, and negative friction are beyond the scope of this discussion and are generally dealt with by the geotechnical engineer of record for the project.

Safety factors are assigned to account for uncertainties from unknown loads or loading conditions, site variations, and inaccuracies in load determination methods. Statistical methods can assess risk, and form the basis for the safety factors (differing values depending on the method of load evaluation) proposed by modern codes.

Safety factors are either (a) "global" for allowable stress designs (ASD), or (b) "partial" for load and resistance factor designs (LRFD). In ASD, the ultimate pile capacity is divided by a global safety factor to find the allowable or working load on the pile, and thus all uncertainty is lumped into this single factor.

LRFD designs recognize different loading conditions have different uncertainty and therefore assigns different "load factors" to these load conditions. For example, the structure's dead weight is known while applied live loadings due to wind, earthquake or temporary loads can be highly variable. Thus load factors for dead weights are lower than for live loads. LRFD methods assign different strength factors (often called "resistance factors" with values less than unity) which relate to the capacity verification procedure reliability. The general expression for LRFD design is

$$\sum \gamma_i \mathbf{Q}_i \leq \mathbf{\Phi}_k \mathbf{R}_k \tag{1}$$

where γ_i is the load factor for the load $\mathbf{Q}_i$ of the ith load type (e.g. for the primary load condition of gravity loading, γ_1 might be 1.4 for the dead load Q_1, and γ_2 might be 1.7 for the live load Q_2), and $\mathbf{\Phi}_k$ is the resistance factor for the resistance $\mathbf{R}_k$ for the kth limit state (e.g. $\mathbf{\Phi}$ might be 0.80 for a static load test $\mathbf{R}$ on 1% of the piles). In concept, for a given set of load and resistance factors, an equivalent global safety factor can be calculated from the load factor divided by the resistance factor (e.g. in the above examples, the equivalent global safety factor is 1.94 for a 50% dead load situation). Although various codes may use differing load factors and differing resistance factors, the resulting equivalent global safety factor may be comparable for a similar distribution of dead to live load ratio. Because some codes are written in terms of ASD only, this paper will convert LRFD code factors into equivalent global safety factors for specific case of primary gravity loading with 50% dead and 50% live loads to allow direct comparisons. Since load factors are lower for dead loads, and generally the total loads are usually more than 50% dead loads, the resulting converted factors are conservative.

The risk of foundation failures makes capacity evaluation necessary. Logically, less testing and less accurate tests increase the risk of a failed foundation, while more testing and more accurate tests reduce risk. The goal of any project design is an acceptably low probability of failure. Piles can potential fail either due to structural failure of the pile itself or geotechnical failure (e.g. soil strength), or because serviceability or deformation limits are exceeded. Generally, driven piles rarely fail structurally because they are "manufactured" under strict quality control, often using relatively high material strengths. Driven piles are installed to a driving criteria based on blow count and thus when obtained at the expected or typical tip elevation gives indirect assurance of a structurally sound pile. Closed end pipe piles can be visually inspected to assure structural integrity. Drilled or augered piles that are cast-in-place have a higher probability of structural failure due to variability in the construction process, and thus usually have higher associated safety factors, or lower **Φ** factors on the structural strength conditions. Deflection limits are also usually indirectly satisfied by selection of a sufficient safety factor on strength.

STATIC LOAD TESTING

Static testing has traditionally been the standard for evaluating soil strength and thus ultimate pile capacity, although many sites had no testing specified, particularly when the number of piles per project was relatively low as would be the case for a small bridge. For projects of sufficient size, prior to about 1970, piles were tested using a slowly applied load maintained over several days to twice the design load, as specified in ASTM D1143. Generally, only one static test was performed per site and these "proof tests" rarely failed. The traditional safety factor of 2.0 was thus established because of this loading to only twice the design load, even though actual safety factors were larger since the pile did not fail. Common failure load evaluations were determined by some pile top movement limit (typically 0.75 to 1.5 inches), or a net movement limit (typically 0.25 to 0.75 inches) after load removal. Due to recent emphasis by the FHWA (1997), the quick procedure static test method detailed in ASTM D1143 is becoming more common, the evaluation for failure or ultimate load uses the offset yield line method (generally among the most conservative of failure definitions), and the loads are often carried to failure or to at least three times design load in a test taking only a few hours.

When the ultimate failure load can be determined, rather than only a proof load, foundation costs can often be reduced. For large projects, special preconstruction test programs are effective. Fewer piles are required when higher loads are proven, or shorter piles can be used. For smaller projects, the first production piles serve as "test piles" and some driving criteria adjustment and cost savings are possible if the piles can be shortened. Production piles are driven to the test pile criteria.

However, since it is not practical to statically test every pile because of time and cost constraints, such testing is usually limited to a very small sample of piles on any site (typically 1% or less on large projects, or only one per site, if any, for small projects).

Static testing accuracy is affected by many factors (Fellenius, 1990). When static testing is performed properly, the measuring accuracy should be within 20% of the true value. The reliability of results is improved if a recently calibrated load cell is specified. However, interpretation of the resulting load-settlement graph (Fellenius,

1990) can give several different ultimate loads depending on the evaluation method (e.g. Davisson, Chin, Butler-Hoy, double tangent, slope, D/10, etc). Interpretation is also affected by displacement measurement inaccuracies; establishing a true reference that is unaffected by the loading process and by the elements (e.g. temperature and solar influences) is a very difficult assignment.

In the extreme case where every pile is tested with a very accurate method (e.g. static load test) with a conservative failure definition, the safety factor can be significantly reduced because the risk is reduced. The offset yield line criteria recommended by the FHWA and the Pile Driving Contractors Association (PDCA) code (PDCA, 2001) is among the most conservative of failure criteria and thus justifies lower safety factors. The PDCA code committee, under the leadership by Dr. G.G. Goble, assigns lower global safety factors for testing more piles, because the uncertainty is reduced. The safety factor varies depending on the amount of testing, ranging from a safety factor of 2.0 for testing only 0.5% of the piles, to a safety factor of 1.65 if 5% of the piles are tested. Piles are selected so site variability is adequately addressed, and adequate hammer performance is periodically verified. A lower safety factor means the pile load can be increased, resulting in fewer piles, or the driving criteria can be relaxed, thus reducing production pile installation time and costs. The extra testing costs are more than compensated by reduced foundation costs.

DYNAMIC PILE TESTING

Dynamic testing was pioneered by Dr. G.G. Goble and his colleagues at Case Western Reserve University in Cleveland Ohio and is now a routine pile capacity evaluation method. Dynamic testing requires measuring pile force and velocity during hammer impact (ASTM, 2000) and subjecting this data to a signal matching analysis to determine the soil behavior. Extensive correlations between static and dynamic testing have verified the method’s reliability (Likins, 1996), and a discussion of accuracy is included in the Appendix. After correlating the static and dynamic tests, the PDCA code allows substitution of three dynamic tests for one static test in determining the quantity of further testing. Thus, with at least one successful correlation, the PDCA suggests that 5% static testing can be translated into testing 15% of the piles dynamically, for the same suggested global safety factor of 1.65. It is probably implicitly assumed that the large number of tests allows site variability to be properly assessed and hammer performance to be evaluated periodically throughout the project duration.

In many cases dynamic pile testing has completely replaced static testing. In this case no site specific correlation is established and there is a higher risk, since the correlation depends upon past experience. This extra risk requires an increased safety factor compared with static testing methods. In this case, the global safety factor in the PDCA code can vary from 2.1 with only 2% of the piles tested dynamically down to 1.9 when at least 10% of the piles are tested dynamically.

To obtain a reliable ultimate capacity from dynamic pile testing, some very basic guidelines must be followed. The hammer input must produce a minimum set per blow so that the soil is loaded sufficiently to mobilize the full soil strength. In cases where the set per blow is very small (e.g. large "blow count"), the dynamic pile test will activate only a portion of the full soil strength and thus will underpredict the true ultimate capacity (this is analogous to a "static proof test"), so the result is conservative. Finally, the pile capacity of driven piles often changes with time after installation (usually increases due to "setup", although in some cases reduction due to "relaxation" are found). To measure these time dependent capacity effects, the driven pile should be tested by restrike after an appropriate waiting time. Restrike tests are recommended standard practice for capacity evaluation by dynamic pile testing.

Dynamic testing provides other benefits for driven piles. Dynamic pile testing provides valuable additional information on driving stresses, which if too large can result in pile damage. Pile integrity can be evaluated dynamically for both location and extent of damage, if any. Proper hammer performance is extremely important for driven piles because engineers rely on the blow count (or set per blow) as a driving criteria for pile acceptance, thus implicitly assuming that the hammer is performing properly. By periodic monitoring throughout larger projects we can assure that the hammer is performing properly and consistently during the entire project so that the same initial driving criteria can be used for all piles with confidence. Periodic testing can check site variability and investigate the cause of piles that are too short or too long or that have unusual blow count records to determine if the cause is the hammer or the pile or the soil. These guidelines for checking site variability and periodic hammer verifications are mentioned in the PDCA code.

Dynamic pile testing is often performed on drilled piles and augercast piles, where the capacity is also time sensitive; the testing must be carried out after the concrete or grout has attained adequate strength, so a sufficient wait to allow the soil strength to recover from the installation process is naturally attained. The generally used procedure is to use a drop weight for the impact so that the drop height and number of blows applied is controlled. A relatively thin plywood cushion (typically 50 to 100 mm) is placed at the pile top to distribute the loads. Usually an initial small impact is applied to check the instrumentation and alignment. Blows with increasing drop height are then applied until either the stresses reach the strength limits of the pile, or until the set per blow exceeds about 3 mm which activates the full capacity, or until the result indicates a capacity sufficiently in excess of the requirements for the project, whichever comes first. The recommended drop weight is at least 1% of the required ultimate capacity to be proved for shafts installed in clay soils or into rock sockets (Hussein, 1996). For piles with larger expected end bearing contributions, the recommended percentage increases to at least 2% of the load to be tested.

WAVE EQUATION ANALYSIS

This computer simulation of the pile driving process has a numerical model which is constructed for the hammer, for the pile, and for the soil. Numerous assumptions are made such as hammer performance and soil response behavior. Assumed ultimate capacities are entered, a one dimensional wave propagation analysis is made, and the resulting blow counts are predicted. A series of assumed resistances and associated predicted blow counts produce a "bearing graph" to establish a suggested driving criteria. However, because of the increased uncertainty associated with the assumptions, the risk is increased and thus the safety factors in the AASHTO (1992) and PDCA codes are suggested as 2.75 and 2.5, respectively.

DYNAMIC FORMULA

These "energy formula" were developed over 100 years ago to estimate pile capacity by simple energy considerations. Some engineers still use them today to make a preliminary selection of hammer size. However, these methods are very simplistic. Numerous studies have concluded that their prediction accuracy is poor (Olsen, 1967), and to minimize risk, large safety factors are necessary. The standard ENR formula for example has a theoretical safety factor of 6. Recent studies have shown that the Gates formula is statistically the best for prediction (Long, 2002). Thus the Gates formula is the only formula currently recognized by the PDCA, American Association of State Highway and Transportation Officials (AASHTO), and the FHWA (although FHWA strongly recommends that dynamic formula be replaced by wave equation analysis). Since the coefficient of variation is relatively high, and the risk increased, the PDCA recommended safety factor for the Gates formula is 3.5.

STATIC ANALYSIS

In the design process, geotechnical engineers estimate pile capacity from soil strength estimates obtained from site soil investigations to obtain a preliminary design length for bidding purposes. Numerous correlations and empirical correction factors for soil strength were developed for SPT, CPT, or other soil sampling tools. However, there is generally considerable scatter in strength prediction results and local experience does not transfer to differing conditions or differing sampling methods. Numerous prediction events have demonstrated that such predictions are generally highly inaccurate, particularly in sandy soil conditions where strength is determined by SPT N-values (Long, 2002). Thus, because of large inherent risk due to poor prediction accuracy, the PDCA code requires a safety factor of 3.5 for piles installed using only a static analysis. In general practice, driven piles are almost never installed to a depth from a static analysis alone, but the final installation is governed by blow count determined by dynamic methods or confirmed by static test.

COMPARISON OF CODES

The various codes, summarized in Table 1, provide an interesting focus for comparison. The PDCA code (PDCA 2001), referenced previously, is the official recommendation of the piling contractors in the USA. The PDCA code's ASD factors originated from the AASHTO Standard ASD code (1992). The percentage of piles tested influences the global safety factor in the PDCA code as already noted.

AASHTO represents the 50 state highway departments and thus covers bridge design in the USA. AASHTO is moving toward LRFD, but the result is still under development. Because of similarities of origin, factors for static analyses and dynamic formula are identical to the PDCA code. AASHTO recognizes that wave

Table 1. Equivalent Global Safety Factors for Various Deep Foundations Codes

Code (1)	EC7 (2)	Australia (3)	PDCA (4)	AASHTO (5)	IBC (6)
Year	2001 (d)	1995 (c)	2001	1992	2000
design load-tons	50% DL	50% DL			>40
static analysis		2.12 to 3.44	3.5	3.50	6.00
Dynamic formula		2.50 to 3.06	3.5	3.50	NA
wave equation		2.50 to 3.06	2.5	2.75	NA
dynamic test (a)				2.25	2.00 (b)
low (# tests)	2.23 (#=2)	2.12 (<3%)	2.1 (2%)		
high (# tests)	1.95 (#>20)	1.72 (>15%)	1.9 (10%)		
static test				2.00	2.00
low (# tests)	2.29 (1)	1.93 (<1%)	2 (<0.5%)		
high (# tests)	1.64 (>5)	1.53 (>3%)	1.65 (>5%)		
static & dynamic (a, b)	(g)	(g)	(e)	1.90	(g)

Code (1)	ASCE driven piles (4)	ASCE driven piles (5)	ASCE driven piles (6)		
Year	1996 (f)	1996 (f)	1996 (f)		
design load-ton	16 to 40	40 to 100	>100		
static analysis	NA	NA	NA		
dynamic formula	2.0 – 2.4	NR	NR		
wave equation	1.8 to 2.2	1.9 to 2.3	NR		
dynamic test (a)	1.6 to 2.0	1.7 to 2.0	2.0 to 2.4		
low (# tests)					
high (# tests)					
static test	1.5 to 1.8	1.6 to 1.9	1.8 to 2.2		
low (# tests)					
high (# tests)					
static & dynamic (a, b)	(g)	(g)	(g)		

Notes: a	dynamic testing requires signal matching
B	requires at least one correlating static test
C	dynamic formula for sands only - not clays
D	draft code
E	3 dynamic tests can be substituted for 1 static test
F	depends on pile type, site variability, load conditions, etc.
G	no specific guidance
NA	not applicable
NR	not recommended

equation analysis is more reliable than dynamic formula so the safety factor is set at 2.75. The AASHTO code for dynamic testing does not specifically mention signal matching and thus may partially account for the relatively high factor 2.25 for dynamic testing. Static testing alone has the traditional standard factor of 2.0. Testing both statically and dynamically results in a lower safety factor of 1.9. Generally the AASHTO code does not address the amount of testing to be performed.

The International Building Code (IBC, 2000) is an effort by the three USA regional building codes to form a single national code covering structures in the USA. The foundation section comes originally from the Southern Building Code (Cobb, 2002) with its base from the 1940's and an update in 1982 to cover "new technology" items missing from the original code (e.g. prestressed piles), but nothing new relating to safety factors. The IBC does provide for dynamic pile testing (as per ASTM D4945) as a new inclusion of this new code. This SBC code is obviously the oldest among the codes discussed in this paper, and generally reflects older practice requirements.

For piles with design loads under 40 tons, capacity is determined by "an approved driving formula", or by static analysis, with no load testing required. The static analysis uses either a soils investigation or a safety factor of 6 referenced to a chart of conservative soil strengths. For loads of 40 tons or higher, wave equation analysis is specified to estimate the driving criteria, and the load is to be verified by either static or dynamic testing (dynamic testing in ASTM D4945 indirectly implies at least one correlating static test).

In contrast to IBC 2000, the Australian Code AS2159-1995 is perhaps one of the most progressive in the world. AS2159 is an LRFD code and the global factors shown in Table 1 for comparison are computed from an equal weighting of live and dead loads (having 1.5 and 1.25 primary load factors respectively), resulting in a generally conservative presentation of global factors. The range of safety factors in the code is given with some guidance by the code. The dynamic formula factors are to be applied to sandy soils only; dynamic formulae are prohibited for clay soils. Factors for static analysis are based on the soil exploration method (e.g. SPT or CPT; CPT methods are given higher confidence and thus lower safety factors). The dynamic testing factors require signal matching. Lower safety factors for dynamic testing require at least 15% of the piles to be dynamically tested (and also comprehensive site investigations and careful construction control), while higher factors are used when less than 3% of the piles are dynamically tested. The lowest static testing safety factors come from statically testing more than 3% of the piles, while higher factors apply when less than 1% of the piles are statically tested.

The Eurocode 7 (draft 2001) is also a progressive LRFD code and the global factors shown here for comparison are conservatively computed from an equal weighting of live and dead loads (having 1.5 and 1.35 primary load factors respectively). In contrast to the PDCA and Australia codes which rely on the ***percentage*** of piles tested, the global safety factor for Eurocode is dependent upon the ***number*** of tests performed. In the opinion of this author, it is preferable to base the number of tests on a percentage of total piles on site when the project requires a substantial number of piles so that site variability and consistency of performance are adequately investigated. Global safety factors for tension loadings are about 10% higher. The factors presented in Table 1 are applied to the ***mean*** result for the tests. Eurocode 7 also specifies separate ***minimum*** factors for comparison with any individual test result. These minimum factors are generally slightly less than the mean factors which allow an individual pile to have a global safety factor less than these mean values. However, if one test result falls below the minimum, that pile must be driven further even if the mean of all tests is acceptable.

The ASCE 20-96 (ASCE, 1997) is the Standard Guidelines for the Design and Installation of Pile Foundations. This code is quite different from others in that the safety factor is defined by three parts (capacity determination method, design axial load levels, and structural pile type). The capacity determination method is the only common criteria with other codes. The criteria related to design load has come under sharp criticism (Cobb, 2002). Because of more structural uncertainty, this code requires significantly higher safety factors for non-driven piles. Determination of capacity solely on static analysis is not recommended for piles with design loads over 40 tons. Except for lightly loaded piles, dynamic formula are not recommended and no factors are even suggested (factors for lightly loaded piles are unrealistically small for the associated risk). The factors for dynamic and static testing are generally similar to PDCA values for lower pile loads, but the factors are higher than the PDCA values for piles with design loads of 40 tons or more.

The ASCE code is currently in a revision process and safety factors are likely to be reduced for the higher load cases. The current 2004 draft provisions remove the criticized dependence on the design load but still relate the safety factor to the pile type which reflects the uncertainty associated with the pile quality and installation process. Closed end steel pipe piles have the lowest safety factors since they can be fully inspected following installation. Factors for other driven piles are slightly higher. Factors for augercast piles and temporarily cased drilled shafts have factors which are still higher, and the highest factors are associated with drilled shafts without temporary casing (and presumably installed with wet methods).

EXAMPLE

Consider a project requiring 20 columns, each with an ultimate column load of 2000 tons. Further, the ultimate load per pile (determined by any method) is assumed to be 200 tons. Using the global safety factors contained in the PDCA code for a static analysis with verification by dynamic formula, the design load for each pile would be 57 tons, requiring 35 piles per column and a total of 700 piles for the project. If the piles are each 60 ft in length and the cost per foot is assumed to be $30 per foot, the total pile cost is $1,260,000. By simply running a wave equation analysis, the global factor drops to 2.5 and the design load per pile can be increased to 80 tons. The project then requires only 500 piles, and the total cost of the foundation piles drops to $901,000 (a savings of $360,000 in return for a $1,000 engineering cost).

For this same example, the cost of a day of dynamic testing is assumed to be $3,000 and that 10 piles are tested per day in restrike (Capacity is usually confirmed by restrike. Cost includes signal matching on about one-third of all piles tested which is typical practice and required by the PDCA code). It is further assumed that the first static test to 200 tons on the project costs $15,000 (which includes the initial mobilization costs), and subsequent tests are then $10,000. Table 2 summarizes the costs of the pile installation and test costs for different combinations of dynamic and static test methods to verify the pile capacity. Depending on the percentage of piles tested and the type of testing, the number of piles required per column drops to between 21 and 17 (actually 16.5 but an integer number of piles per column is required), and the design loads increase to 95 to 121 tons. The total cost, including testing, then ranges from $759,000 with relatively minimal dynamic testing, to $745,000 with minimal static testing, down to $642,000 with an extensive mix of dynamic and static testing. Thus with even with minimal dynamic or static testing, the total foundation costs are reduced by over $450,000. With sufficient testing the total foundation savings exceed $600,000. Thus, the investment in testing provides cost savings which benefit the project costs and more than justify the testing. While the total costs would vary when other codes are used, the general conclusion that testing substantially reduces the total costs would remain the same.

Table 2. Project Cost Analysis

Capacity Verification Method (1)	PDCA Safety Factor (2)	Design Load per Pile (T) (3)	Total Piles per Project (4)	Pile Cost $ (5)	Testing Cost $ (6)	Total Cost $ (7)
dynamic formula	3.50	57 tons	700	1,260,000	100	1,260,100
wave equation	2.50	80	500	900,000	1,000	901,000
dynamic test (2%)	2.10	95	420	756,000	3,000	759,000
dynamic test (10%)	1.90	105	380	684,000	11,400	695,400
static test (0.5%)	2.00	100	400	720,000	25,000	745,000
static test (2%)	1.80	111	360	648,000	75,000	723,000
static test (1) + dynamic (6%)	1.80	111	360	648,000	21,480	669,480
static test (1) + dynamic (15%)	1.65	121	340	612,000	30,300	642,300

This example clearly demonstrates the potential savings available. It does assume that the pile length remains unchanged and thus that the soil conditions are favorable to this assumption (e.g. a clearly defined bearing layer exists). Cost savings are still likely to be substantial even if the piles must be driven a little deeper.

There are other means for cost savings. There is a trend to increased design loads on the same pile section. As a result of increased testing, the design loads for the same concrete pile sections in Sweden have doubled since the late 1970's (Gravare 2000). Recent efforts in the USA have resulted in doubling of design stresses on several projects (Miner 2001, and Frazier 2002). It should be noted in the former case, that savings were estimated at $1,500,000, and in the later case that the savings were only about 35% of the total cost because the piles were driven a little deeper to gain the extra capacity and the number of piles can be reduced by half only when there is an even number of piles in every column. Design stress increases should only be permitted when driveability by wave equation is confirmed, and when the soil conditions are favorable, and when the ultimate loads verified by testing.

Other savings have been noted by reducing the pile lengths for the same design load from the original project design (based on static analysis). Testing at various times both at end of driving and during restrike after a waiting period can quantify setup, a soil strength gain with time after driving, which can be effectively used in the pile design (Komurka 2002). By taking advantage of strength gains (only possible with sufficient testing) smaller hammers, shorter piles, higher loads can be used, and considerable savings can result. Cost savings can be quantified by looking at "support costs" which are defined as cost per unit load (Komurka 2003), and the foundation solution (pile type and pile length) determined for the lowest possible foundation cost. In another recent case, for example, the savings resulted in a substantially reduced pile length (over 35,000 ft saved for the project) and a cost savings of over $1,000,000 for the project (Lee 2003). This length savings further resulted in eliminating pile splices for most piles, and the reduced time required for installing the shorter lengths and elimination of splices resulted in keeping the installation scheduling on track.

CONCLUSIONS

Keeping the risk of foundation failure below an acceptable level is the goal for any foundation. To accomplish this, safety factors are applied to the ultimate pile capacity to calculate an acceptable design or working load for the piles. The risk of failure can be reduced by testing more piles, or using evaluation methods that are more accurate. A reduced risk of failure justifies lower safety factors.

As a common practice, static analysis methods are generally only used to estimate pile lengths in the design process. Rarely are pile installations governed by this method, so whether a code has a factor or not for static analysis is almost a non-issue. Dynamic formulae are also decreasing in usage. They remain mainly a tool for preliminary hammer selection. In most cases, actual use of dynamic formula to govern pile installation is perhaps limited to projects with few piles and light design loads. From a practical view, a wave equation analysis is almost as fast and simple as a dynamic formula, and result in cost savings from a lower safety factor specified in the codes. Generally some other more precise method (wave equation, dynamic testing, or static testing) is also specified on most projects, particularly projects with design loads above 40 tons, so the lower safety factor and improved reliability of the more accurate methods would then govern the project anyway.

The safety factors recommended by several newer codes generally give a range of safety factors depending on the type and amount of testing performed on site, and result in factors less than the traditional factor of 2.0. These more modern testing methods, combined with a higher frequency of testing and the resulting lower safety factors, can substantially reduce the total foundation costs.

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APPENDIX

The accuracy of dynamic testing capacity predictions has been the subject of many past studies. In order to reliably use the dynamic testing results, many have compared the dynamic testing results with static load tests on the same piles. Of course both should be run to failure (e.g. have a sufficiently large permanent set), and ideally both would be performed with similar wait times after installation so that known strength changes with time would be minimized.

Table A1 statistically compares the dynamic testing results with signal matching (e.g. CAPWAP) against static load tests for three major studies. In the original study by Goble (1980) containing 77 driven piles, the average CAPWAP result was 1.01 times the static load test, and a 0.168 coefficient of variation (COV) which measures the dispersion of results or reliability. The 1996 study (Likins, 1996) for 83 other driven piles had an average ratio of 0.931 with a similar COV reliability (0.166) for the normal “best match” analysis. The radiation damping model gave an average closer to unity for the 1996 data and a very low COV (but should be restricted to displacement piles with moderate to high blow counts). The fully “automatic” computer optimization (with no user input) gave very good results for the 1996 data.

A review of all six previous Stresswave (SW) Conferences results in a database of such information. It was found that the average of 143 additional correlations was a ratio of 0.993 with a COV of 0.165. The COV for driven piles was lower, probably due to better known pile properties and more test cases, than for drilled shafts and CFA piles. It is also interesting and understandable that better correlations (lower COV values) are obtained when the time ratio of dynamic testing (during restrike) after installation is more similar to the time of static testing (e.g. generally requires dynamic testing at least 5 days after installation). While the 1980 and 1996 results always used the Davisson criteria to evaluate the static test, the author’s failure evaluation procedure was often unknown in the Stresswave study. In some cases, the static load test curve and the simulated static test from CAPWAP were available. Comparison of the CAPWAP result and the static result, each at a deflection of 20 mm, results in an average ratio of 0.968 with a COV of only 0.101. From this analysis it would appear CAPWAP does an excellent job of predicting the load versus displacement behavior at lower loads (e.g. working loads) in the elastic zone.

Combining all studies, the average ratio for 303 piles was 0.98 with a COV of 0.169. The comparison of this correlation is shown in Figures A1 and A2. It should be generally noted that correlation of one definition of failure versus another on the same piles results in similar statistical confidence (Paikowsky 2000), and thus it could be concluded that CAPWAP is statistically similar to other evaluation procedures.

The Davisson method is among the most conservative of all evaluation procedures, and thus there is often additional reserve strength present. Thus evaluations with Davisson and CAPWAP are generally considered conservative. Lower safety factors would be appropriate for conservatively evaluated static tests.

Table A1. Statistical Evaluation of Dynamic Pile Testing

Study (1)	avg (2)	cov (3)	n (4)	Notes (5)	Time Ratio (Dynamic to Static) (6)
1980	1.010	0.168	77	original Goble study	
1996	0.964	0.223	83	automatic only	
1996	0.931	0.166	83	Best Match	
1996	1.012	0.097	83	radiation damping	
1996	1.019	0.092	61	radiation damping	dynamic/static > 0.25
SW	0.993	0.165	143	all piles	
SW	0.983	0.156	119	all driven	
SW	1.037	0.199	23	all drilled and cfa	
SW	0.972	0.147	45	all piles	dynamic/static > 0.25
SW	0.910	0.183	96	all piles (CW/max)	
SW	0.968	0.101	24	all piles CW/SLT@20 mm	
All	0.980	0.169	303	(1996 data uses "best match" method)	
2000	0.930	0.146	75	static versus static – Paikowsky	

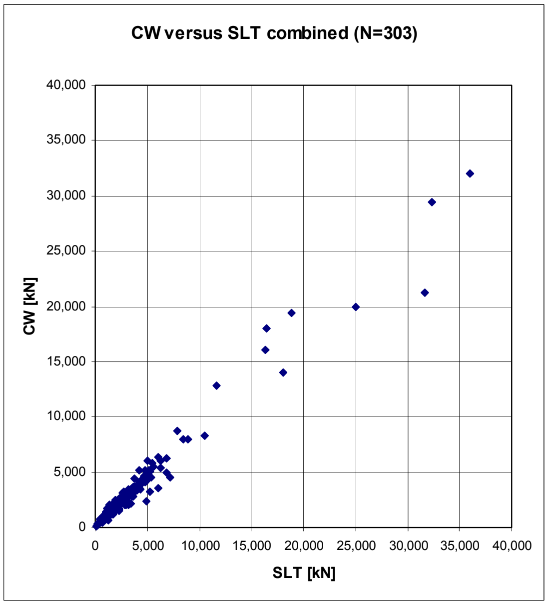

FIG. A1. Correlation of All Studies

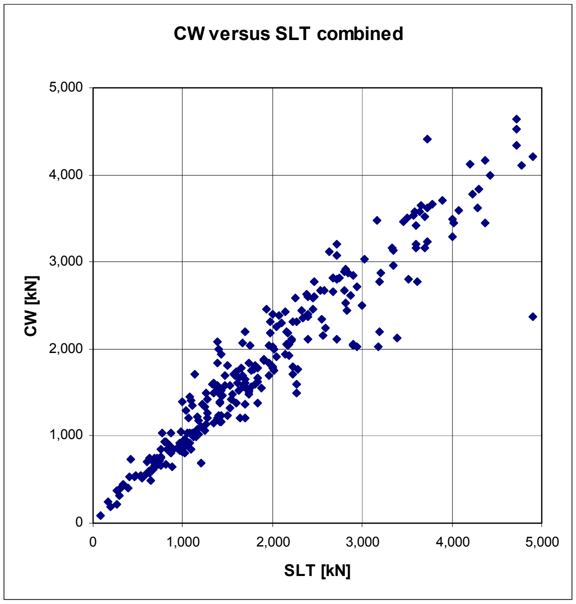

FIG. A2. Correlation of All Studies: Detail of Lower Capacity Correlation