Safety Factors for Pile Testing

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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 settlements. The required pile capacity also depends on the test method for verification of the pile capacity and the frequency of testing. This paper compares safety factors contained in the PDCA's "Recommended Design Specifications for Driven Bearing Piles" with factors from other published codes.

Safety factors are assigned to lower the risk of foundation failure. They compensate for uncertainties from unknown loads or loading conditions, from site variations and from inaccuracies in load determination methods. Additional geotechnical considerations like consolidation in compressible layers and negative friction are beyond the scope of this discussion. Statistical methods can be employed to assess risk. These statistical methods form the basis for the safety factors proposed by modern codes such as the PDCA code.

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

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

$$\Sigma \gamma_i Q_i \leq \Phi_k R_k$$

Where γ_i is the load factor for the load Q_i of the ith load type (e.g. 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 Φ_k is the resistance factor for the resistance $\mathbf{R}_k$ for the kth limit state (e.g. Φ might be 0.80 for a static load test **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). Further mention of LRFD in this article will use computed equivalent global factors.

The risk of foundation failures makes capacity evaluation necessary. Logically, less testing increases the risk of a failed foundation, while more testing reduces risk. Similarly, more accurate test methods reduce risk, while less accurate methods increase risk. The goal is an acceptably low probability of failure. Piles can potentially fail either due to structural failure or geotechnical failure (e.g. soil strength). Generally, driven piles rarely fail structurally (drilled or augered piles have a higher probability of structural failure and thus usually have higher associated safety factors, or lower γ factors on the structural strength conditions).

Static Load Testing has traditionally been the standard for evaluating soil strength and ultimate pile capacity. Prior to about 1970, piles were loaded using a slow maintained load procedure 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

Global Safety Factors - Allowable Stress Design Values

Australia

Code	**PDCA**	AASHTO	IBC 2000	AS2159-95	ASCE (20-96) for driven pile types			ASCE
year	**2001**	1992	2000	1995	1996			(non-driven piles)
design loads			>40T		16 to 40 T	40 to 100T	>100T	>100T
static analysis notes:	**3.50**	3.50	6.00	2.12 to 3.44	NA	NA	NA	NA
dynamic formula notes:	**3.50**	3.50	NA	2.50 to 3.06 c	2.0 to 2.4 h	NR	NR	NA
wave equation notes:	**2.50**	2.75	NA	2.50 to 3.06	1.8 to 2.2 h	1.9 to 2.3 h	NR	NA
dynamic testing notes:	**1.9 to 2.1** **a**	2.25	2.00 b	1.72 to 2.12 “a, f, g”	1.6 to 2.0 h	1.7 to 2.0 h	2.0 to 2.4 h	2.6 to 3.6 h
static testing notes:	**1.8 to 2.0** **d**	2.00	2.00	1.53 to 1.93 “f, g”	1.5 to 1.8 h	1.6 to 1.9 h	1.8 to 2.2 h	2.3 to 3.2 h
static & dynamic notes:	**1.65 to 1.9** **“a, b, e”**	1.90	j	j	j	j	j	j

Notes

a dynamic testing requires signal matching
b requires correlating static test
c dynamic formula for sands only - not clays
d <2% static
e >1% static or >3% dynamic
f higher SF if <3% dynamic or <1% static
g “lower SF if >15% dynamic or >3% static, and extensive site investigation with careful construction control”
h “depends on pile type, site variability, load conditions, etc.”
j not specifically addressed
NA - not applicable
NR - not recommended

failed. The traditional safety factor of 2.0 was thus established because of this loading to only twice design, 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, the quick procedure static test method detailed in ASTM D1143 is becoming common, the evaluation for failure or ultimate uses the offset yield line method, and the loads are often carried to failure or to at least three times design in a test taking only a few hours. The PDCA code follows this guidance.

When the ultimate failure load can be determined, rather than only a proof load, foundation costs can be potentially 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, it is not practical to statically test every pile because of time and cost constraints. Therefore, static testing is usually limited to a very small sample of piles on any site (typically 1% or less on large projects, or often only one per site, if any, for small projects).

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 can give several different ultimate loads depending on the evaluation method (e.g. Davisson, Chin, Butler-Hoy, double tangent, slope, D/10, etc).

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 PDCA code is among the most conservative of failure criteria and thus justifies lower safety factors.

The PDCA code awards lower safety factors for testing more piles, because the uncertainty is reduced. For testing only 0.5% of the piles, a safety factor of 2.0 is suggested, while if 5% of the piles are tested, then the safety factor can be reduced to 1.65. Piles are selected so site variability is adequately addressed, and adequate hammer performance is periodically verified. Lower safety factors means the pile load can be increased, resulting in fewer piles, or that 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 is a routine pile capacity evaluation method. Dynamic testing requires measuring pile force and velocity during hammer impact 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. 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, then the PDCA suggested 5% static testing can be translated into testing 15% of the piles dynamically, for the same suggested safety factor of 1.65. The large number of tests allows site variability and hammer performance consistency to be properly assessed.

In many cases, dynamic pile testing has completely replaced static testing. In this case, no site-specific correlation is established and thus there is a higher risk, since the correlation depends upon past experience of the signal matching analysis accuracy. This extra risk requires an increased safety factor compared with static testing methods. In this case, the safety factor 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 be sufficiently large to produce a minimum set per blow so the soil is loaded plastically and thus mobilizes the full soil strength. In cases where the set per blow is very small (e.g. large "blow count"), the dynamic pile test will only activate a portion of the full soil strength and thus will under-predict the true ultimate capacity (this is analogous to a "static proof test"), so the result is conservative. Finally, the pile capacity often changes with time after installation (usually increases due to "setup," although in some cases reduction due to "relaxation" are found). To measure time dependent capacity effects, the 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. 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 monitoring periodically throughout larger projects, it can be assured 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.

Wave Equation Analysis is a computer simulation of the pile driving process. A numerical model 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 factor in the PDCA code is suggested as 2.5.

Dynamic 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 and, to minimize risk, large safety factors are necessary. The standard ENR formula, for example, has a built-in safety factor of 6. Recent studies have shown that the Gates formula is statistically the best for prediction. The Gates formula is the only formula currently recognized by the PDCA, AASHTO, and the FHWA (although FHWA strongly recommends that dynamic formula be replaced by wave equation analysis). Since accuracy is relatively poor and risk increased, the recommended safety factor by PDCA for the Gates formula is 3.5.

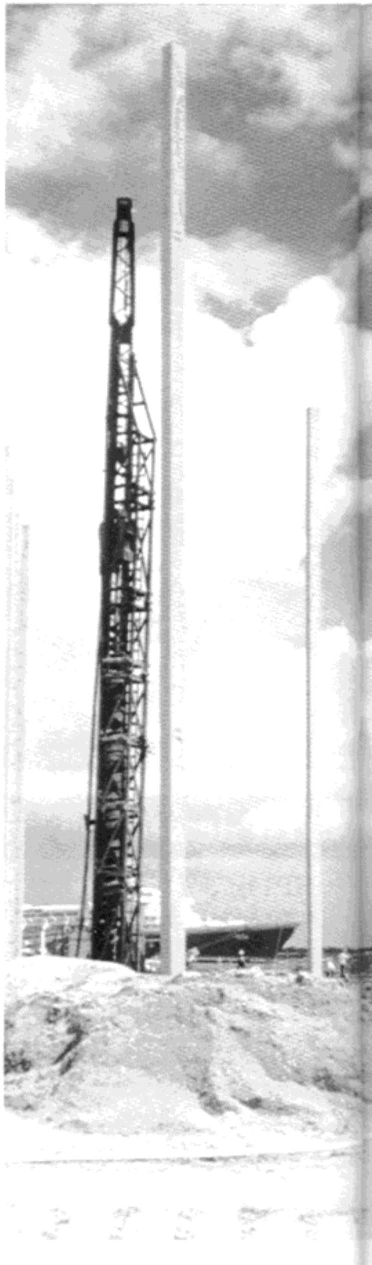
Static Analysis estimates pile capacity from soil strength estimates obtained from site soil investigations. Numerous correlations and empirical correction factors for soil strength were developed for SPT, CPT, or other soil sampling tools. However, there generally is considerable scatter of strength 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. Because of large inherent risk due to poor prediction accuracy, the PDCA code requires a safety factor of 3.5 for piles installed to a static analysis criteria only for an acceptable level of risk.

Comparison of the PDCA Code with Other Codes is summarized in the accompanying table and provides an interesting platform for discussion. The PDCA code origin started with the AASHTO Standard ASD code from 1992.

AASHTO (American Association of State Highway and Transportation Officials) represents the 50 state highway departments plus the FHWA. Subsequently, AASHTO is moving toward LRFD but the result is still under development. Because of similarities of origin, factors for static analysis and dynamic formula are identical to the PDCA code. AASHTO recognizes that wave equation analysis is more reliable than dynamic formula so the safety factor is set at 2.75. 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.

IBC 2000, from the International Building Code, is an effort of the three USA regional building codes to form a single national code. The foundation section comes originally from the Southern Building Code which has its base from the 1940s with an update in 1982 to cover a few "new technology" items missing from the original code (e.g. prestressed piles, et al), but nothing new relating to safety factors. The IBC did provides for dynamic pile testing (as per ASTM D4945) as a new inclusion of this new code. This SBC code is obviously the oldest 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 here for comparison are computed from an equal weighting of live and dead loads (having 1.5 and 1.25 load factors respectively). 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 formula 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 result 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 ASCE 20-96 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 latter two criteria have come under some recent criticism ("Proposed Overhaul of Deep Foundation Provisions of the International Building Code" by Len Cobb, presented at the ASCE Geo-Institute Deep Foundations 2002 Conference, Feb 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 permitted. 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. (This code is currently in a revision process and safety factors are likely to be reduced for the higher load cases).

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 formula 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 are perhaps limited to light design loads. From a practical view, a wave equation analysis is almost as fast and simple as a dynamic formula. 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.

In summary, 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. 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 reduce the total foundation costs. ▼