The Role of Full Scale Testing in ASD and LRFD Driven Pile Designs

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ABSTRACT For design of foundations on driven piles, Load and Resistance Factor Design (LRFD) is increasingly replacing the conventional Allowable Stress Design (ASD) approach. LRFD separates the uncertainty in loading conditions from the uncertainty in resistances, while the ASD approach uses a single "global factor of safety" to cover all uncertainties. Concerning resistances, LRFD uses a range of "resistance factors" adjusted to the method of capacity evaluation and level of quality control and assurance during construction, while the previous ASD approach often considers only the method of capacity evaluation but not the amount of testing. Considerable confusion exists as to how to best apply the new LRFD methodology and reap its potential benefits to affect a safe and economical foundation. This paper attempts to address some of the issues and answer questions associated with the newly implemented method.

The benefits of full scale pile testing, by either static or dynamic methods, and of an increased amount of such testing, are illustrated by numerical examples. After a review of the global factors of safety for different codes, pile designs using ASD global factors of safety are compared with designs produced using the most recently developed LRFD resistance factors from AASHTO Specifications. Among the capacity evaluation methods will be static analysis, dynamic formula, wave equation, dynamic testing and static testing. Although the prime emphasis is the AASHTO specification, comparisons are also made with resistance factors from current standards from Europe, Australia, and Canada.

INTRODUCTION

When designing a foundation, engineers have many choices, including pile capacity, pile size (type, length and diameter), and number of piles to support the structure loads. The 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 method used to determine the pile capacity and the amount of testing.

The design may employ either (a) allowable stress design (ASD) or (b) load and resistance factor design (LRFD). Both ASD and LRFD procedures are intended to avoid foundation failure. They compensate for uncertainties in applied loads, site variability and inaccuracies in capacity determination methods. In ASD, the ultimate pile resistance is divided by a global factor of safety (F.S.) to find the allowable or working load on the pile, lumping all uncertainty into this single factor. In LRFD various applied "load factors" (larger than unity) are assigned to the applied loads, and different "resistance factors" (Φ – smaller than unity) reflect the capacity determination method's reliability.

The American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration (FHWA), issues a guide design specification. State Departments of Transportation can individually adopt this AASHTO guide specification (AASHTO 2010) as a whole, modify it, or create their own standards and specification.

Historically, AASHTO's design specification was ASD based. AASHTO's first proposed LRFD specification in 1991 was unsatisfactory. The first LRFD version used was in 1994 (Dasenbrock et al. 2009). AASHTO announced in 2000 that after October 2007 bridge foundation design required LRFD methods. A second generation AASHTO LRFD specification was then produced in about 2005 with some relatively minor edits by 2007. Based on industry review, the resistance factors were updated in 2010.

This paper compares design practices under ASD (AASHTO, 1992) with that under the 2010 version of AASHTO LRFD, with specific emphasis on changes to the resistance factors. Mention of the AASHTO LRFD practice until the mandatory 2007 date is brief and is included for historical interest and for highlighting the recent changes in the 2010 specification. Comparison is also made between the current AASHTO specification, the Eurocode, and the Canadian and Australian LRFD standards.

CAPACITY DETERMINATION METHODS

The following is a summary of the load determination methods for driven piles which are in the generally perceived order of increasing accuracy: static analysis, dynamic formula, wave equation analysis, dynamic testing, and static testing. All except static analysis are really a "testing" since they require information obtained during or after pile installation (dynamic formula and wave equation analysis require blow count, dynamic testing measurement of force and motion and static testing measurement of load and settlement). However, capacity is only one aspect of design. For example, designs must produce tolerable settlements. Such additional design considerations like settlement, seismic liquefaction, scour, consolidation in compressible layers, lateral loading, and downdrag loads are beyond the scope of this discussion.

Static Analysis estimates pile capacity from soil strength parameters obtained from site subsurface geotechnical investigations. While this is a necessary initial step in any foundation design so that a preliminary design can be made for bidding purposes, rarely would static analysis be the only tool to determine capacity since there generally is considerable scatter of both soil strength determination and pile capacity prediction. Local experience does not transfer to differing conditions on sites far from the experience base or differing sampling methods or to use of equipment not in the engineer's past experience, in addition to potential errors in the modeling procedures and computational methods.

Because static analysis predictions are statistically highly inaccurate (which is why the AASHTO specification resistance factors are low), to produce an economic design, the static analysis is almost always used in conjunction with a tests method and the higher resistance factor of the test method will then control the design. Further, the 2010 AASHTO Commentary mentions static analysis predictions tend to significantly overestimate the capacity for larger diameter piles, and therefore recommends either static or dynamic testing when piles larger than 24 inch diameter are anticipated.

Piles are rarely installed to a specified depth based on static analysis alone. Specifications should not impose minimum embedment depths based on static analysis computations to assure capacity, but instead minimum depth requirements should be limited to cover only concerns such as scour, settlement or lateral support. Indeed most driven pile specifications require a minimum blow count criterion at termination of driving.

Dynamic Formulas, developed over a century ago to estimate pile capacity, are overly simplistic and should be limited to piles with relatively low capacity. Numerous studies have concluded that their capacity prediction accuracy is poor, and thus their usage is declining. In the US highway industry the Gates formula is currently preferred and recognized by AASHTO and the FHWA (although FHWA strongly recommends that dynamic formula be replaced by wave equation analysis).

Wave Equation Analysis simulates the pile driving process. Using a numerical model of the hammer system, the pile, and the soil, numerous assumptions are made including hammer performance and soil response to pile penetration during driving or during restrike. For a series of assumed capacities (e.g. ultimate resistances), the resulting corresponding blow counts are calculated, resulting in a "bearing graph". For variable stroke hammers (e.g. diesel or hydraulic hammers) a series of stroke values can be specified as input and the resulting corresponding blow counts computed for the desired capacity, producing an “inspector’s chart”. In a “drivability analysis”, the pile capacities computed from a static analysis at a series of different penetration depths and analyzed to obtain the predicted blow counts as a function of pile penetration. Because the wave equation analysis is more realistic than dynamic formula, a higher resistance factor is allowed. However, this factor is smaller than the factors for the still more accurate dynamic or static testing methods.

Dynamic Pile Testing, as specified in ASTM D4945 (ASTM 2010), routinely evaluates pile capacity on private and public works projects, including State highway projects, by measuring pile force and velocity during hammer impact and subjecting this data to a signal matching analysis to evaluate the soil behavior (Likins and Rausche, 2008). To obtain the full capacity from dynamic pile testing, the net penetration per blow should normally exceed 0.1 inch (2.5 mm) or the full soil strength may not be mobilized. To account for time-dependent capacity effects, the pile should be tested by restrike after an appropriate waiting time. For the usual case with “setup”, capacity at the end of drive will be conservative. The most efficient design will verify the capacity during a restrike dynamic test to take advantage of the capacity increase due to setup (Komurka 2003), incorporating this extra capacity into the design. For the relatively rare case where capacity reduces after installation, such as piles driven into weathered shale (Morgano 2004), capacity should be taken from restrike tests as the AASHTO 2010 design specification correctly mentions.

Dynamic pile testing on designated test piles or periodically on production piles throughout larger projects provides valuable additional information on pile driving stresses, pile integrity, and on hammer performance. Dynamic driving stresses that exceed pile material strength cause structural pile damage. Monitoring the hammer system performance level is important for driven piles because engineers usually rely on the blow count (or net penetration per blow) as a driving criterion for pile acceptance, thus implicitly assuming that the hammer is performing properly, or at least consistently, so that the same initial driving criterion can be used for all piles with confidence.

Static Loading Tests, as specified in ASTM D1143 (ASTM 2007), have traditionally been the standard for evaluating pile capacity. Prior to about 1970, in general only one static test was performed per site using a slow maintained load procedure over several days to only twice the design load. Such tests rarely failed, thus establishing the traditional safety factor of 2.0, even though actual safety factors were often much larger. Due to recent emphasis on accelerated construction by the FHWA, the quick static test method taking only a few hours has become common. In the quick test the capacity evaluation uses the Davisson offset limit line method, and the test is often carried to failure or to at least three times design load. This potentially reduces foundation costs because fewer piles or shorter piles can be used. The Davisson criterion recommended by the AASHTO specification for driven piles is among the most conservative of failure criteria, providing an additional degree of safety to current estimates.. However, because of time and cost constraints static testing is usually limited to a very small sample of piles on any site (typically 1% or less on large projects and one test pile or none at all on small projects).

For large projects, preconstruction test programs with static and/or dynamic testing are effective for optimizing the foundation reliability and economy. Because dynamic testing is much less costly, on many projects, static testing may be replaced by more dynamic pile tests, which has the added benefit of allowing site variability to be more efficiently assessed. For smaller projects, the first production piles serve as "test piles" and some driving criteria adjustment and cost savings are often possible, e.g. if the piles can be shortened. Production piles are driven to the criterion of the successful test pile.

AASHTO

ASD Past Practice

Driven pile design begins with a subsurface investigation and initial selection of pile type, size and length) based on a static analysis. Prior to 2007, State DOTs foundation design (ASD) for piles often used a single global factor of safety (F.S.). The global factor of safety depended on the type of capacity determination method. Methods perceived to be more accurate resulted in lower safety factors and therefore resulted in fewer piles required to support any given load. The following table lists F.S. for different determination methods (AASHTO, 1992), and the number of piles required for a hypothetical example of a 2,000 ton structure (17,820 kN) with 200 ton (1,782 kN) capacity piles. The design load per pile is computed based on the determination method selected (e.g. for static testing and applying a F.S. of 2.0, design load is 200÷2.0 = 100 tons, which then requires that 20 such piles are needed for the 2,000 ton total load). Implied in this comparison is the assumption that the various methods have the same statistical bias, i.e. while they have a different scatter, the average is more or less the same capacity.

TABLE 1. Pre-2007 AASHTO ASD factors of safety (F.S.) design loads (for a 1782 kN or 200-ton capacity) and number of piles required (for a 17,820 kN or 2,000-ton structure)

Determination method	F.S.	Design load KN/ pile (tons)	Number of Piles required
Dynamic formula	3.5	508 (57)	35
Wave equation	2.75	650 (73)	28
Dynamic testing	2.25	793 (89)	23
Static testing	2.0	891 (100)	20
Static & Dynamic testing	1.9	935 (105)	19

A required number of dynamic or static testing was not specified, however, once the testing phase was finished, a blow count criterion was established and the production piles, driven to that criterion, were also effectively tested. Clearly, with the lower F.S. for higher level testing. the number of required piles was significantly reduced, and, since the cost of the piles was much more than the cost of testing, a great economic savings was usually achieved.

It should be mentioned that the International Building Code (IBC, 2009) uses an ASD approach and that the global factor of safety for either static or dynamic testing is 2.0. No specification is made for the amount of testing required.

LRFT Basic Formulation

The general expression for LRFD design is

$$\sum \gamma_i Q_i < \Phi_k \mathbf{R_k} \quad (1)$$

Where Q_i = is the load for the i[th] load type
γ_i = is the load factor of the i[th] load type (e.g. AASHTO load factors for the generally governing Strength 1 case are γ_i = 1.25 for the dead load Q_1, and 1.75 for the live load Q_2, reflecting the relative uncertainty of these loads),
$\boldsymbol{R_k}$ = is the resistance defined by the k[th] determination method
Φ_k = is the resistance factor for the k[th] determination method (e.g., the AASHTO resistance factor is 0.75 for a static load test).

In concept, for any given set of load and resistance factors, an equivalent global factor of safety can be calculated from the weighted average load factor divided by the resistance factor. For example, in the generally governing Strength 1 limit case, with D/L = 3 (D is dead load, and L is live load) and Φ = 0.75, the equivalent global factor of safety F.S. is 1.83. F.S. will be lower for higher D/L ratios, and higher for lower D/L ratios. This reflects the uncertainty in loading conditions which is a clear advantage of LRFD over ASD. It should be noted that for D/L ratios above 7, the governing condition is Strength 4 which has a load factor of 1.5 on dead load only.

AASHTO 2007 LRFD Design Specification

In October 2007, when LRFD was mandated, the then current AASHTO design specification (AASHTO 2007) required assessment of site variability, generally determined from statistical analysis of SPT results, which seemingly ignored that piles are generally driven to a predetermined blow count to mitigate site variability. The generally low resistance factors for driven piles in this AASHTO 2007 specification, often resulted in more piles than resulted from the earlier ASD specifications. Therefore, the 2007 AASHTO resistance factors led to considerable concern in the driven pile industry, and confusion among some State DOTs on how to implement these requirements, and concerns about their effects on project costs.

2010 AASHTO LRFD Design Specification

The driven pile industry, represented by the Pile Driving Contractors Association (PDCA) including both contractors and engineers, worked with AASHTO to institute a review of the 2007 specification and tried to reflect past successful practice for driven piles to the relevant sections specifically addressing driven piles (AASHTO Sections 10.5 and 10.7). It was recognized and agreed that since the previous ASD practice was highly successful in producing safe designs, the LRFD specification did not need to be more conservative. Resistance factors in the LRFD specification, producing designs similar to previous ASD designs, were therefore considered a reasonable objective.

The 2010 AASHTO guide design specification (AASHTO, 2010) is simplified from the 2007 version. The resistance factors in Section 10.5 now reflect the common practice that almost all driven piles are installed to a minimum blow count criterion. This blow count criterion automatically compensates for normal site variations so that where the soil strengths are low the piles will be driven deeper until the required driving resistance is reached and comparable to the test piles. Assessing site variability and using the approach described by Paikowsky (2004) is still an option, as mentioned in the Commentary. Furthermore, the resistance factor reduction due to limited redundancy was moved to the Commentary with the definition of redundancy left to user discretion (guided by a limit from 2 to 5 piles) and the suggested Φ reduction limited to at most 20 % for driven piles. It should be realized that very few bridge foundations would have this reduction applied since, for piers on driven piles, the number of piles per pier is well above any redundancy limit.

Table 2 summarizes the recommended AASHTO 2010 resistance factors and reanalyzes the example of Table 1 (200 ton [1782 kN] capacity piles and 2,000 ton [17,820 kN] structure load) with the commonly used D/L of 3. The dead and live loads of 1500 and 500 tons (13,365 and 4,455 kN), respectively are multiplied by their load factors of 1.25 and 1.75 to obtain the factored load of 2750 tons (24,503 kN). The capacity (called "nominal resistance" and assumed constant for all capacity assessment methods) is multiplied by the resistance factor (Φ) to obtain the factored resistance per pile for the particular capacity determination method. The resulting number of piles (rounded up to nearest integer) can then be computed from the total factored load divided by the factored resistance per pile. The equivalent ASD factor of safety is shown by comparison (assuming Strength 1 case and D/L = 3).

Specifically, the dynamic formula for Φ = 0.4 is the Gates Formula and is applicable to the end of drive condition only. The number of piles required is equivalent to the ASD case as shown in Table 1. The Commentary suggests that in general dynamic testing should be conducted (during restrike) in lieu of using dynamic formula.

For the wave equation analysis, the resistance factor is 0.5. This results in an equivalent F.S. and identical number of piles to the ASD case as shown in Table 1. However, because of the uncertainty in actual hammer performance, the 2010

AASHTO specification requires some field determination of hammer performance (e.g. direct measurement of stroke or kinetic energy). This is particularly important for the variable stroke hydraulic hammers, and even diesel hammers. If hammer performance measurements are not made, the Commentary recommends reducing the resistance factor to 0.4, the equivalent of a dynamic formula.

TABLE 2. 2010 resistance factors (Φ), factored resistance (200 ton or 1782 kN capacity) and number of piles required (for 2000 ton or 17,820 kN structure with typical D/L = 3)

Determination method	Φ	Equivalent F.S.	Factored resistance kN (ton) / pile	Number of piles required
Dynamic formula (Gates)	0.4	3.44	713 (80)	35
Wave equation	0.5	2.75	891 (100)	28
Dynamic testing (2% or 2#)	0.65	2.12	1,158 (130)	22
Static testing or 100% Dynamic testing	0.75	1.83	1,337 (150)	19
Static & 2% Dynamic testing	0.8	1.72	1,426 (160)	18

Dynamic testing alone is assigned an Φ of 0.65, and specifically now states that a minimum of either 2 piles, or 2% of all piles, be tested "per site condition". The specification defines a site condition as a geologically similar soil condition and states that in highly variable soils a site might consist of a single pier. The 2010 AASHTO specification specifies that dynamic testing include "signal matching" (e.g. CAPWAP®), and notes that best estimates of capacity come from testing during a restrike (allowing soil strength changes to have occurred; e.g. common setup or less frequent relaxation). The Commentary notes dynamic testing results at end of driving are generally conservative, and notes that if relaxation is anticipated these resistance factors should only be used with restrike results. The Commentary further notes that an increase in safety (decrease in uncertainty) results if the most heavily loaded piles are selected for dynamic testing. The 2010 factors result in an equivalent global F.S. of 2.12, and therefore a slight decrease in the number of piles required for the example foundation compared with the former ASD specification.

Static testing is assigned a Φ of 0.75, and again requires a test for each site condition. Since static testing is relatively expensive, the amount of testing is generally limited, so a more extensive discussion of site variability is provided in the Commentary. Dynamic testing of 100% of all piles, the best means for assessing site variability, is assigned the same Φ as static testing for a single pile for one site condition. In the example, the equivalent global F.S. is 1.83 and results in a 5% reduction in the number of piles required per site (2010 LRFD Table 2 versus ASD Table 1), and 17% fewer piles for 100% dynamic testing.

The reduced risk from the combination of static testing plus dynamic testing for each site condition results in an increase in the Φ to 0.8. The same minimum testing requirements apply (i.e. one static test plus dynamic testing of 2% of all piles, or two piles, whichever is greater). The dynamic tests are to be calibrated to the static tests either by preferably determining an appropriate damping factor for the site or by ratio of results. The 0.8 Φ is equivalent to a global F.S of 1.72, and results in a 5% reduction in number of piles required per site compared with the ASD specification. If no dynamic testing is done during production pile installation then the Commentary recommends reducing the Φ from 0.8 to 0.75.

Further Discussion of AASHTO 2010

The changes to the resistance factors in the 2010 AASHTO specification lead the specification back toward designs consistent with previous ASD practice. Since the previous practice for driven piles over the past several decades was deemed successful (e.g., lack of failures), LRFD results that are consistent with ASD solutions are also deemed appropriate. Certainly there is no need to be more conservative.

The minor 5% reduction in number of piles required in a design when tested statically (or in combination of static plus dynamic) is considered an acceptable risk given that:

1. Few static tests fail, and the Davisson criterion is among the most conservative methods to assign nominal resistance from a static test. Further, most static tests have still considerably more reserve strength beyond the Davisson failure load.
2. Set-up is very common (even in sands) and adds extra safety for driven piles. Since most static tests are run after only modest wait times, longer waits may result in significant extra capacity. This is even more true for dynamic tests which are usually performed for the typical modest size highway project at end of drive or during a restrike after a few hours or at most a few days.
3. Production piles always exceed the driving criterion (e.g. diving to a required 47 blow/foot, often the pile experiences 47 blows well before the full foot, resulting in extra capacity); or requiring that the blow count criterion be met for two feet of pile penetration usually results in the pile being driven to higher resistance.
4. Production pile driving may result in densification of the soil, improving previously driven piles, particularly for piles driven in loose granular soils. This is one reason why interior piles are often driven first in a group of piles.
5. Preliminary designs often overestimate the actual loads. Few piles are actually critically loaded, yet all are driven to the same higher load criterion and thus have extra capacity (AASHTO correctly requires testing the critically loaded piles). Finally the number of piles in a group is rounded up (e.g. 8.4 piles required would be rounded to 9).
6. The use of a higher Φ for driven piles compared to other deep foundation types is justified considering that:
   a. Foundations on driven piles have very limited history of failures (beyond scour or downdrag conditions that are now considered as separate issues).

b. Driven piles generally are subjected to a significant testing effort (static and/or dynamic), and must satisfy a "blow count" criterion, making every driven pile a "tested" pile and allows driven pile lengths to adapt well to site variability.

7. "Signal matching" is required by AASHTO for dynamic tests. CAPWAP, the commonly used signal-matching program, is compared in Figure 1 with the Davisson criterion as shown, and the conservatism of Davisson is discussed in Point 1 above. However, fewer than 9% of all CAPWAP (CW) results exceed the maximum applied load of a Static Load Test (SLTmax) as shown by the "Ratio" (in percent) in Figure 2, which further highlights discussion Point 1 above.

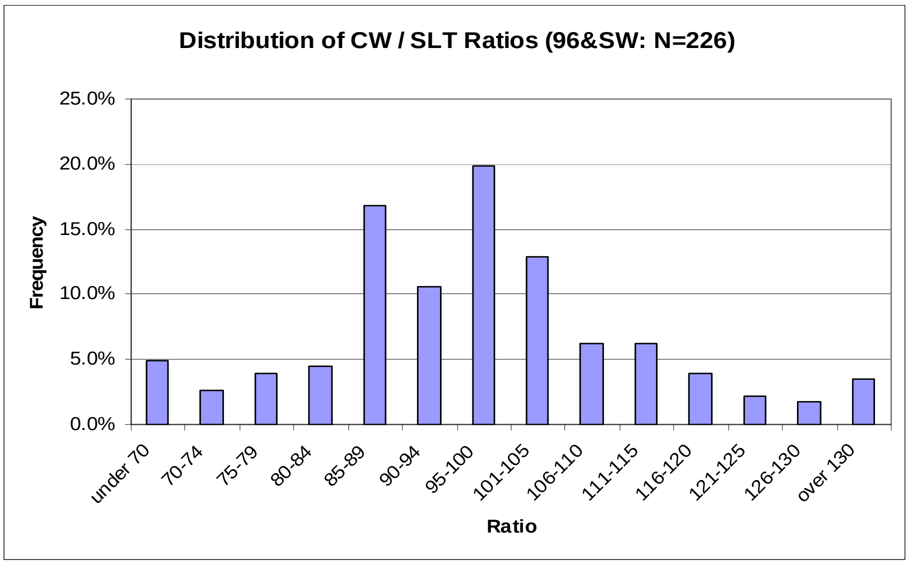

Fig. 1. Distribution of ratios (in percent) of CAPWAP to Static Load Test (SLT) at the Davisson criterion (after Likins 2004)

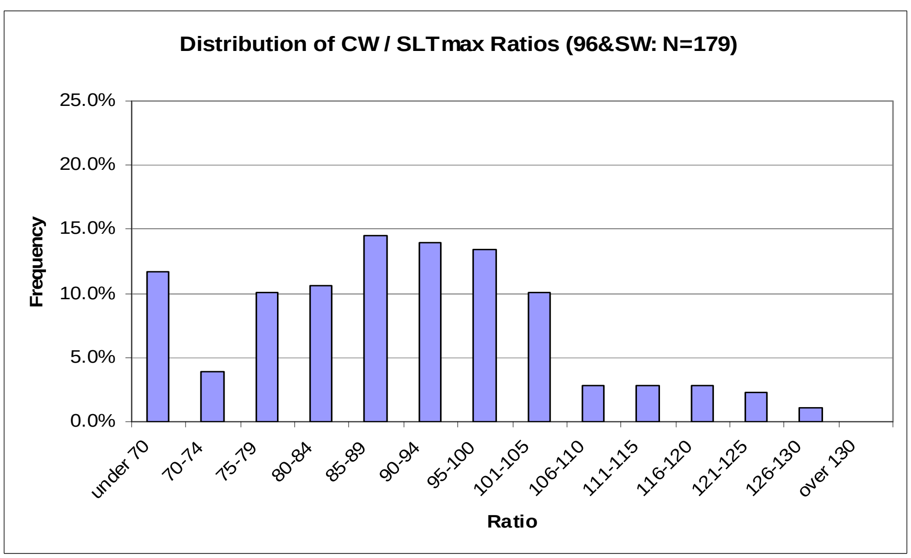

Fig. 2. Distribution of ratios (in percent) of CAPWAP to maximum applied Static Load Test (SLT) (after Likins 2004)

The above discussion demonstrates that there is a cumulative conservatism in a driven pile foundation.

The AASHTO 2010 specification lists specific resistance factors for the minimum 2% dynamic testing (0.65) and for complete 100% dynamic testing (0.75). The question could be raised as to what resistance factor would be appropriate for some intermediate yet significant percentage of dynamic testing (e.g. 5%, 10%, 15%, 25% or even 50% dynamic testing of all piles). The PDCA technical committee had, for example, also recommended to include for simplicity an intermediate category of 25% dynamic testing with an Φ of 0.70 (20 piles would be required for our hypothetical example and, therefore, 5 would have to be tested). Such a logical intermediate category could be adopted by any State DOT. Any DOT might also adopt a linear interpolation of the Φ depending on percentage of piles tested between 2% and 100%. The Australian standard (discussed later) has a formula relating Φ to the percentage of piles tested.

When implementing LRFD, many State DOTs have relatively little experience in selecting appropriate resistance factors for various nominal resistance determination methods. Hopefully they will wisely adopt the new 2010 AASHTO recommendation for the greatest economic benefit which means that the testing effort should not only be used to perform a required test, but also to use the gained knowledge for the current and future designs. This is particularly important when taking advantage of modern high strength pile materials and pile installation equipment.

These AASHTO 2010 resistance factors are recommended upper limits. If a specific project is particularly sensitive or has particularly difficult soil conditions, the engineer may opt to reduce the resistance factor which, in general, will add some foundation cost, but the normal site should not be penalized for the occasional unusual condition.

Resistance factors that produce a more conservative design than the previous AASHTO ASD should be rejected since, as stated, there are no known capacity failures for driven piles based on ASD provisions. It is the authors' contention that, with time and experience, future AASHTO recommendations may allow higher resistance factors for the well proven and conservative driven piles. For example, the Ohio Department of Transportation has increased Φ to 0.70 for dynamic testing, rather than the AASHTO guide of 0.65.

EUROCODE

The US is not the only country which has taken to the LRFD approach. The Eurocode uses a partial factor approach . The action case A1 uses load factors of 1.35 on dead loads and 1.50 on live loads. The average load factor (LF) is multiplied by a "resistance factor" (always 1.15 for driven piles in compression loading) and by a "correlation factor" to obtain a "global factor" to be used like the ASD factor of safety. The correlation factor (CF) depends on the type and amount of testing according to Table 3. For our hypothetical example, these factors result in the required numbers of piles as shown in Table 3. The amount of testing required is expressed in absolute numbers and not in percentages of piles on the project.

TABLE 3. Equivalent Factors of Safety for Eurocode and number of piles required (for 200 ton or 1,782 kN capacity pile and 2,000 ton or 17,820 kN structure for a typical D/L = 3)

	Amount of static testing (by number of tests, #)				
	1	2	3	4	5
CF	1.4	1.3	1.2	1.11	1.0
Equiv F.S. (D/L = 3)	2.23	2.07	1.92	1.77	1.60
# piles required	23	21	20	18	16
	Amount of dynamic testing (by number of tests, #)				
	2	5	10	15	20
CF	1.36	1.28	1.23	1.21	1.19
Equiv F.S. (D/L = 3)	2.17	2.04	1.96	1.93	1.90
# piles required	22	21	20	20	19

It is interesting in the Eurocode that the equivalent F.S. for static tests has such a large range depending on the amount of static testing. One reason could be that the Eurocode is applicable to all kinds of structures and that the code writers had in mind primarily large building foundations rather than size limited piers like in a bridge foundation. Compared with AASHTO, Eurocode results in more piles required for minimum static testing, but considerably fewer if there are 5 or more static tests. For dynamic testing as the control method, the number of piles required is comparable to the AASHTO result. There is no resistance factor for a combination of static plus dynamic testing, and thus no direct incentive to perform both tests on a site, but clearly there is a distinct economic advantage for more testing of either kind.

AUSTRALIAN STANDARD

Australia developed their first LRFD standard AS2159 in 1995 and it was used successfully for many years. It has been recently updated in 2009 (Standards Australia, 2009). The primary load factors governing most compressive pile designs are 1.2 for dead load and 1.5 for live load. For our example with D/L of 3, the factored load becomes 2,550 tons (22,720 kN). For D/L ratios above 10, the governing condition has a load factor of 1.35 on dead load only.

The resistance factor (Φ) is computed from a formula that includes a variety of factors including nine individual risk factors (such as site variability, soils investigation completeness, experience in similar geological conditions, design method assessment, construction control, among others), redundancy consideration, an intrinsic test factor, and the percentage of piles tested. As it turns out, as the percentage of piles tested approaches a limit (10% static testing, or 25% dynamic testing), the resistance factor approaches the intrinsic test factor (0.9 for static testing, and 0.8 for dynamic testing). That is reasonable since sufficient testing greatly reduces the unknowns and, therefore, the risks. The Φ then becomes the constant intrinsic test factor and, as a result, the fewest number of piles are then required. Dynamic testing always requires signal matching (e.g. CAPWAP) in this standard.

Table 4 gives a brief example of how to use the Australian standard. For both static and dynamic testing, at any given test percentage, four Φ values are given: the highest value for lowest risk, the lowest value for the highest risk condition; the intermediate Φ values approximate the "typical" risk condition for high and low redundancy which is the most likely use (high redundancy is defined as 5 or more piles per group). Piles for most bridges would use the "high" redundancy factor, resulting in fewer piles.

TABLE 4. 2010 resistance factors (Φ), factored loads (for a 200 ton or 1,782 kN capacity pile) and number of piles required (for a 2,000 ton or 17,820 kN structure with typical D/L = 3)

Determination method	Φ	Equivalent F.S.	Factored resistance kN/pile (ton)	Number of Piles required
Static testing (0.5%)	.79	1.63	1,408 (158)	17
	.65	1.95	1,158 (130)	20 high
	.59	2.17	1,051 (118)	22 low
	.50	2.53	891 (100)	26
Static testing (1.0%)	.80	1.59	1,426 (160)	16
	.69	1.84	1,230 (138)	19
	.64	2.00	1,194 (134)	20
	.57	2.24	1,016 (114)	23
Static testing (2.0%)	.83	1.54	1,479 (166)	16
	.75	1.70	1,337 (150)	17
	.71	1.79	1,265 (142)	18
	.66	1.93	1,176 (132)	20
Dynamic testing (1.0%)	.77	1.65	1,372 (154)	17
	.65	1.95	1,158 (130)	20
	.59	2.15	1,051 (118)	22
	.52	2.45	927 (104)	25
Dynamic testing (2.0%)	.78	1.64	1,390 (156)	17
	.69	1.88	1,230 (138)	19
	.64	1.99	1,140 (128)	20
	.58	2.19	1,034 (116)	22
Dynamic testing (4.0%)	.79	1.62	1,408 (158)	17
	.72	1.76	1,283 (144)	18
	.69	1.84	1,230 (138)	19
	.66	1.95	1,176 (132)	20
Dynamic testing (10.0%)	.794	1.62	1,417 (159)	17
	.77	1.66	1,372 (154)	17
	.76	1.68	1,354 (152)	17
	.74	1.72	1,319 (148)	18

For the dynamic test, if there is a satisfactory correlation with a static test, then the dynamic intrinsic test factor is increased to 0.85 which further reduces the number of piles required and equivalent safety factor below the values in above Table 4.

CANADIAN STANDARD

The Canadian Code originated initially in 1979 and is called an Ultimate Limit States code (ULS), but operates in a similar manner as the AASHTO LRFD code (Canadian Standard Council 2006). This code is applied not only to highways, but to all structures throughout Canada. The primary loading case for premanufactured driven piles is 1.1D plus 1.7L. The code specifically mentions dynamic formulae are discouraged and therefore lists no resistance factor. For the approved methods, Table 5 summarizes the resistance factors and equivalent factors of safety for D/L = 3, and lists the number of piles required for the example case presented for other codes. The number of piles to test is selected by the designer.

TABLE 5. Canadian 2006 resistance factors (Φ), factored resistance (200-ton or 1,782 kN capacity) and number of piles required (for 2,000 ton or 17,820 kN structure with typical D/L = 3)

Determination method	Φ	Equivalent F.S.	Factored resistance KN/pile (ton)	Number of piles required
Wave equation	.4	3.13	713 (80)	32
Dynamic testing	.5	2.50	891 (100)	25
Static testing	.6	2.08	1,069 (120)	21

COMPARISON OF RESULTS

Comparing all five standards, there is good similarity in the resulting number of piles for our hypothetical test case, as observed in Table 6. The two AASHTO specifications (ASD and LRFD) give identical solutions, implying that the past successful ASD practice will not result in less efficient designs under LRFD. Unlike other codes that are based on a percentage of piles tested, based on a specific number of tests, the Eurocode requires the same number of piles with their minimal amount of dynamic testing, and for static testing the number of piles required depends on the amount of testing, but brackets AASHTO; for the largest amount of static tests, the fewest piles required for any standard are obtained (16). For the Australian standard and the typical risk case and a typical percentage of pile tests, the number of piles required is similar to AASHTO for static tests, or in static and dynamic test combination. But the number of piles required is reduced (by about 10%) for dynamic testing with signal matching in the Australian Code. There are significant cost savings for dynamic testing more piles (the cost of testing is much less than the cost of the piles) in these four codes. The Canadian Code is the most conservative, resulting in the highest cost foundation. The Canadian Code obviously has room for improvement which could result in significant cost savings.

TABLE 6. Code comparison: number of piles required (2,000 ton or 17,820 kN structure, 200 ton or 1,782 kN capacity pile, assuming a typical D/L ratio of 3)

	Number of piles required for example case				
	AASHTO ASD	AASHTO LRFD	Eurocode	Australia AS 2159	Canadian
Dynamic formula	35	35			
Wave equation	28	28			32
Dynamic test Max (2# or 2%)	22	22	22 2#	19 or 20 (2%) (high or low redundancy)	25
Dynamic test 100%		19		17 (10%)	
Static test	19	19	23 to 16 1# to 5#	19 or 20 (1%) (high or low redundancy)	21
Dynamic test and Static test	18	18		18 to 20 (2%) (high or low redundancy)	

CONCLUSIONS

The conversion of AASHTO from ASD to LRFD design procedures has been a long process and not particularly well understood by those selecting resistance factors. Driven piles by their nature of installation have considerable inherit conservatism compared with other foundation elements. The construction method allows for additional conservatism by highly economical dynamic testing. Static testing further enhances the driven pile safety, though at a higher cost.

Since the ASD method had served the industry well, LRFD solutions need not result in more conservative designs that result in more expensive foundations. The 2010 AASHTO recommendations remove the extra conservatism of the earlier LRFD specifications and produce designs that are more consistent with the well proven ASD solutions, and with LRFD standards from Europe and Australia; the Canadian Code is conservative. Thus, while basically a method that is built on statistical considerations, the LRFD method has now been calibrated to traditional design methods. It is hoped that with more experience and improved design and construction control methods, LRFD will allow the driven pile to become an even safer and more economical foundation.

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