The 2010 AASHTO LRFD Resistance Factors

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The American Association of State Highway and Transportation Officials (AASHTO) recently issued an updated Load and Resistance Factor Design (LRFD) design guide specification (AASHTO 2010). As the name implies, LRFD applies factors to both the loads and the resistances, reflecting their individual uncertainties, rather than a single global factor of safety as in the conventional Allowable Stress Design (ASD) approach. LRFD is replacing the ASD approach, and AASHTO has mandated that all bridge projects after October 2007 be designed with LRFD methods.

State Departments of Transportation can individually adopt this AASHTO guide specification, modify the guide specification, or create their own LRFD design specification. Technical Committee T-15 of the AASHTO Bridge Committee is responsible for the foundation sections governing driven piles, and specifically the resistance factors given in Section 10.5.5 of the code. Additional considerations such as scour, lateral loading, consolidation in compressible layers and downdrag loads are beyond the scope of this discussion, but are detailed in Section 10.7 of the 2010 AASHTO code.

Although AASHTO's first LRFD code was in 1991, the first LRFD version applied was in 1994 (Dasenbrock, 2009). After limited use of the early LRFD code, AASHTO announced in 2000 that after October 2007 bridge foundation design required LRFD methods. In anticipation of this mandate, a revised AASHTO LRFD code was produced in 2005 with some relatively minor edits in 2007. Based on industry review by PDCA, the resistance factors in Section 10.5.5 were substantially changed in 2010.

This article compares design from ASD (AASHTO, 1992) with the new 2010 version of AASHTO LRFD, with specific emphasis on changes to the resistance factors for the methods of capacity determination commonly available.

The pile's ultimate capacity is called "nominal resistance" in the AASHTO LRFD code (the term used in the remainder of this article). Let's first quickly list the nominal resistance determination methods for driven piles as specified by 2010 AASHTO which are in perceived order of increasing accuracy. They are:

- static analysis
- dynamic formula
- wave equation analysis
- dynamic load testing
- static load testing

Static Analysis estimates nominal resistance from site soil investigation information. While this is necessary to obtain a preliminary design for bidding purposes, rarely would static analysis be the only tool to estimate nominal resistance and govern installation. Because static analysis is statistically highly inaccurate, driven piles are almost always installed using a more accurate determination method (and the more accurate method will then control installation). Further, the 2010 AASHTO commentary of Section 10.5 mentions static analysis tend to significantly overestimate the nominal resistance for larger diameter piles, and recommends either static or dynamic testing for piles larger than 24 inch diameter.

Dynamic Formula, developed over a century ago to estimate nominal resistance, are very simplistic and have poor prediction accuracy, and thus the AASHTO resistance factors are relatively low. The Gates formula is the preferred formula currently recognized by AASHTO.

Wave Equation Analysis simulates the pile driving process using a numerical model of the hammer, the pile, and

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the soil. For a series of assumed nominal resistances, the resulting blow counts are predicted, resulting in a "bearing graph" relating blow count to nominal resistance.

Dynamic Pile Testing routinely evaluates nominal resistance on DOT projects by measuring pile force and velocity during hammer impact and subjecting this data to a signal matching analysis to determine the soil behavior. For dynamic pile testing to mobilize the full soil strength, the set per blow should exceed 0.1 inch (2.5 mm). To account for time dependent soil strength changes, the pile should be tested after an appropriate waiting time. For the usual case with capacity increase with time, or "setup", the commentary notes nominal resistance at the end of drive will be conservative.

Static Load Testing has traditionally been the standard for evaluating nominal resistance. Prior to about 1970, only one static test, if any, was performed per typical site, often using a slow maintained load procedure over several days to only twice the design load. Since the test rarely failed, this established the traditional safety factor of 2.0, even though actual safety factors were often much larger. Promoted by the FHWA, the quick static test method taking only a few hours has become common, and the nominal resistance evaluation uses the relatively conservative Davisson offset yield line method. 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, or often only one per project, if any, for small projects).

For large projects, preconstruction test programs with static or dynamic testing are effective. On many projects, static testing may be replaced by more cost effective dynamic pile tests, allowing site variability to be better assessed. 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 criteria of the successful test pile.

AASHTO past practice – ASD

Prior to 2007 most State DOT designed driven pile foundations with ASD with a single global factor of safety (F.S.) which depended on the method of nominal resistance determination. Methods perceived to be more accurate resulted in lower safety factors and therefore fewer piles required to support any given load. Table 1 lists F.S. for different determination methods (AASHTO, 1992), and the number of piles required for a hypothetical example of a 2000 ton structure and piles with 200 ton nominal resistance. The design load per pile is computed based on the determination method selected (e.g. for static testing and 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 2000 ton total load).

Determination method	F.S.	Design load Per pile	Number of Piles required
Dynamic formula	3.5	57	35
Wave equation	2.75	73	28
Dynamic testing	2.25	89	23
Static testing	2.0	100	20
Static & Dynamic testing	1.9	105	19

Table 1: pre-2007 AASHTO ASD factors of safety (F.S.), design loads (for a 200 ton nominal resistance) and number of piles required (for a 2000 ton structure)

No quantity of testing was specified for dynamic or static testing. But clearly when some testing was done, the number of piles is significantly reduced, and since the cost of the piles is generally significantly more than the cost of testing, a great economic savings was usually achieved when at least some piles were tested.

LRFD basic formulation

The general expression for LRFD design is

$$\sum \gamma_i Q_i \leq \Phi_k R_k$$

Where γ_i is the "load factor" for the load Q_i of the ith load type (e.g. AASHTO load factors for the generally governing Strength 1 case are 1.25 for the dead load Q_1, and 1.75 for the live load Q_2, reflecting the relative uncertainty of these loads), and Φ_k is the "resistance factor" for the resistance R_k determined by the kth determination method (e.g. AASHTO resistance factor is 0.75 for a static load test).

For any given set of load and resistance factors, an equivalent global factor of safety (F.S.) can be calculated from the weighted average load factor divided by the resistance factor. In the preceding paragraph example for the Strength 1 limit case, the equivalent F.S. is 1.83 for a common D/L = 3 distribution. The equivalent F.S. will be lower for higher D/L ratios, and higher for low D/L ratios, reflecting the uncertainty in loading conditions which is an advantage of the LRFD method. For D/L ratios above 7, the Strength 4 condition governs and has a single load factor of 1.5 on dead load only.

AASHTO 2007 LRFD design code

In October 2007 when LRFD was mandated, the then current AASHTO design code (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 blow count to mitigate site variability. A 20% reduction in the resistance factor was required if the foundation unit had fewer than five piles, and a 40% reduction was applied for single pile foundation units. The generally low resistance factors for driven piles in this AASHTO 2007 code, often resulted in more piles even though there were no failures under the previous ASD code. There was also some concern about the allowance of a safety factor as low as 1.53 for a few situations. Therefore, the 2007 AASHTO resistance factors led to considerable concern in the driven pile industry, particularly among PDCA members, and confusion among some State DOTs on how to implement these requirements, and concerns of their effects on project costs.

Determination method	R.F.	Equivalent F.S.	factored resistance per pile	Number of Piles required
Dynamic formula (Gates)	.40	3.44	80	.5*
Wave equation	.50	2.75	100	28
Dynamic testing (2% or 2#)	.65	2.12	130	22
Static testing or 100% dynamic testing	.75	1.83	150	19
Static & 2% Dynamic testing	.80	1.72	160	18

Table 2: 2010 resistance factors (R.F.), factored loads for the example case

2010 AASHTO LRFD design code

The PDCA technical committee, including both contractors and engineers, worked with the AASHTO T15 Committee in charge of the foundation code to institute a review of the 2007 code and tried to reflect the successful ASD past practice to the sections specifically addressing driven piles (10.5 and 10.7). Resistance factors in the LRFD code Section 10.5.5 that produce designs similar to previous ASD designs were considered a reasonable objective. After considerable discussion between PDCA and AASHTO T-15 committees, the PDCA recommendations were generally approved.

The 2010 AASHTO LRFD guide specification (AASHTO, 2010) is simplified from the 2007 version. The resistance factors in Section 10.5.5 now reflect the common practice that most all driven piles are driven to an installation criterion that includes a blow count. This blow count criterion accounts for site variations automatically; where the soil strengths are relatively low, the piles will be driven deeper until the blow count is sufficient (e.g. comparable to the test piles). Assessing site variability (Paikowsky, 2004) as in the 2007 code is still an option, as mentioned in the commentary. The resistance factor reduction due to limited redundancy was moved to the commentary with the

* NOTE from the Author: This table was printed incorrectly. The number of piles required for Dynamic Formula (Gates) should be 35 not .5.

defined limit number of piles left to user judgment (with guidance of 2 to 5 piles as the limit) and the maximum reduction limited to at most 20% for driven piles.

Table 2 summarizes the recommended resistance factors. The same example is analyzed (200 ton nominal resistance piles and 2000 ton structure load - 1500 tons dead load and 500 tons live load for the given D/L ratio of 3, and with load factors of 1.25 dead and 1.75 live, resulting in a factored load of 2750 tons) and the nominal resistance is multiplied by the resistance factors (R.F.), allowing the required number of piles (rounded up to nearest integer) and the equivalent ASD factor of safety (assumes Strength 1 case) to be computed.

Specifically, the Gates dynamic formula for R.F. 0.40 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 0.50. 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 code requires some field determination of hammer performance (e.g. direct measurement of stroke or kinetic energy) to use this best resistance factor. If hammer performance measurements are not made, the commentary recommends a resistance factor to 0.4, the equivalent of a dynamic formula.

Dynamic testing alone has a R.F. of 0.65, and specifically now states that 2% of all piles, but a minimum of 2 piles, be tested "per site condition". The code states geologically similar soil conditions define a "site condition", and states that in highly variable soils a site might consist of a single pier. The 2010 AASHTO code specifies that dynamic testing include "signal matching" (e.g. CAPWAP), and notes that best estimates of nominal resistance come from testing during a restrike (allowing soil strength changes of common setup or less frequent relaxation to have occurred). The commentary points out that dynamic testing results at end of driving are generally conservative, and notes that if relaxation is anticipated that these resistance factors should only be used with restrike results. The commentary further states that an increase in safety 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 (for D/L = 3), and therefore a slight decrease in the number of piles is required for the example foundation compared with the former ASD code.

Static testing is assigned a R.F. of 0.75, and again requires a test for each site condition. Since the amount of static testing is generally limited, a more extensive discussion of site variability is provided in the commentary. Dynamic testing of 100% of all piles, the ultimate in assessing site variability, is assigned the same 0.75 resistance factor. The equivalent global F.S. is 1.83 and results in a 5% reduction in the number of piles required per site with static testing compared with the ASD code.

The reduced risk from the combination of static testing plus dynamic testing for each site condition allows an increase in the R.F. to 0.8. The same minimum testing requirements (one static test, plus dynamic testing of 2% of all piles, or two piles, whichever is greater) apply. The dynamic tests are to be calibrated to the static tests. The 0.80 R.F. is equivalent to a global F.S of 1.72, and results in a 5% reduction in number of piles required for our example case compared with the ASD code when the site has both static and dynamic testing. If dynamic tests are not employed during production pile installation then the commentary recommends reducing the R.F. to 0.75.

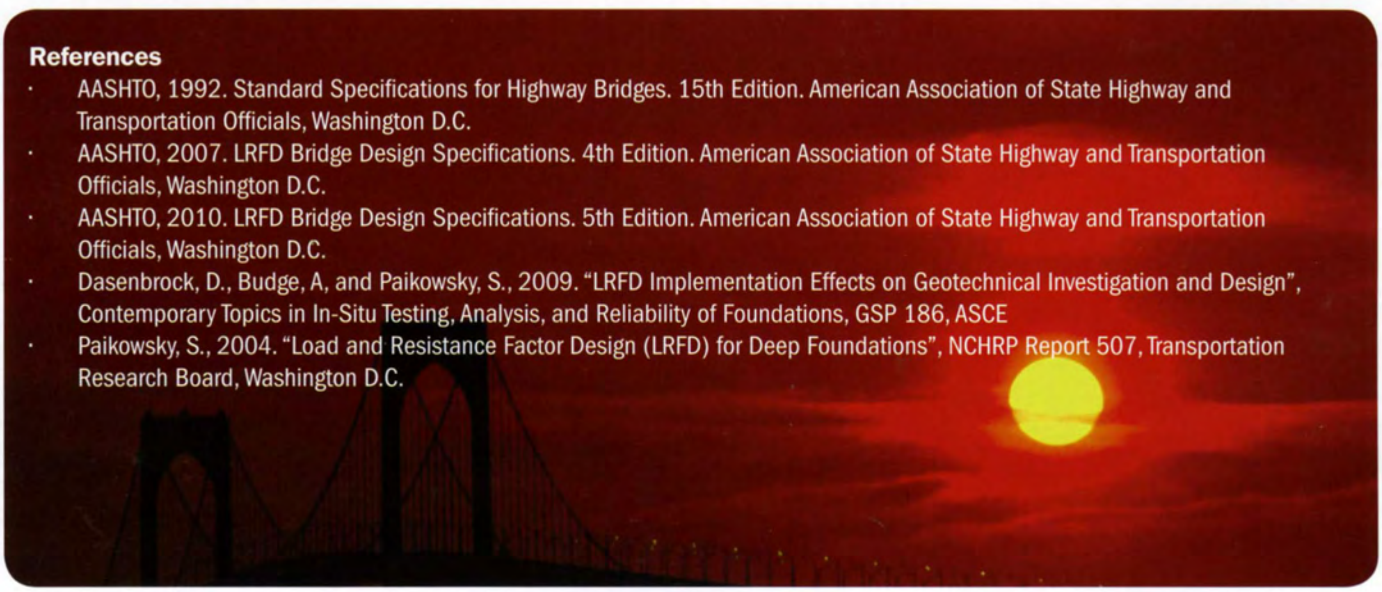
Further discussion

The changes to the resistance factors in the 2010 AASHTO code lead the code 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, and thus more costly.

The AASHTO 2010 code 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. 10%, 25% or 50% dynamic testing of all piles). The PDCA had also recommended an intermediate category of 25% dynamic testing with an R.F. of 0.70 (20 piles would be required for our hypothetical example). Such a logical intermediate category could be adopted by any State DOT.

When faced with implementing LRFD, many State DOTs have relatively little experience or confidence in selecting the appropriate resistance factors for various nominal resistance determination methods. They will hopefully adopt the new 2010 AASHTO recommendation. These resistance factors are the maximum allowed. If a specific project is particularly sensitive or has particularly difficult soil conditions, the engineer may opt to reduce the resistance factor (and result in extra piles installed), but the normal site should not be penalized for the unusual condition. Resistance factors that produce a design more conservative than a design produced by the previous AASHTO ASD should be therefore rejected since there are no known failures for driven piles based on ASD provisions. With time and experience, perhaps future AASHTO recommendations will include even higher resistance factors for the well proven and conservative driven piles.

In conclusion, the conversion of AASHTO from ASD to LRFD has been a long process. Since the ASD method had served the industry well and produced no failed foundations for several decades, LRFD solutions need not result in more conservative designs that result in then more expensive foundations. The 2010 AASHTO recommendations remove the extra conservatism of the earlier LRFD codes and produce designs that are consistent with the well-proven ASD solutions. ▼



References

- AASHTO, 1992. Standard Specifications for Highway Bridges. 15th Edition. American Association of State Highway and Transportation Officials, Washington D.C.
- AASHTO, 2007. LRFD Bridge Design Specifications. 4th Edition. American Association of State Highway and Transportation Officials, Washington D.C.
- AASHTO, 2010. LRFD Bridge Design Specifications. 5th Edition. American Association of State Highway and Transportation Officials, Washington D.C.
- Dasenbrock, D., Budge, A, and Paikowsky, S., 2009. "LRFD Implementation Effects on Geotechnical Investigation and Design", Contemporary Topics in In-Situ Testing, Analysis, and Reliability of Foundations, GSP 186, ASCE
- Paikowsky, S., 2004. "Load and Resistance Factor Design (LRFD) for Deep Foundations", NCHRP Report 507, Transportation Research Board, Washington D.C.