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Verification of Recommended Load and Resistance Factor Design and Construction of Piles in Cohesive Soils

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Abstract

To enhance regional design and construction practices for driven piles, FHWA permitted the development of regional resistance factors for the design of foundation piles. By fitting allowable stress design safety factors to the load and resistance factor design (LRFD) framework, several state departments of transportation (DOTs), including the Iowa DOT, have adopted interim procedures. Subsequently, an LRFD procedure that incorporates setup was developed for piles in cohesive soils through comprehensive research in Iowa. The proposed LRFD procedure used an Iowa DOT in-house static analysis method and the wave equation analysis program for construction control. To verify the adequacy of the proposed procedure and investigate its economic implications, differences in pile design between the interim and the proposed LRFD procedures were evaluated on the basis of independent data collected from more than 600 production steel H-piles driven in cohesive soils. This study concluded that the proposed LRFD procedure would not significantly increase the design and construction costs. The incorporation of pile setup into the LRFD procedure was found to provide additional economic benefits. Although the current Iowa DOT policy is to drive piles to the contract length, if a suitable pile termination procedure were used once the desired resistance was achieved, a general saving of 20% in pile length would be anticipated for both procedures. Although the research and findings presented in this paper are specific to a local area, these methods could be adopted nationally to increase the efficiency of bridge foundations for all states.

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Comments

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To enhance regional design and construction practices for driven piles, FHWA permitted the development of regional resistance factors for the design of foundation piles. By fitting allowable stress design safety factors to the load and resistance factor design (LRFD) framework, several state departments of transportation (DOTs), including the Iowa DOT, have adopted interim procedures. Subsequently, an LRFD procedure that incorporates setup was developed for piles in cohesive soils through comprehensive research in Iowa. The proposed LRFD procedure used an Iowa DOT in-house static analysis method and the wave equation analysis program for construction control. To verify the adequacy of the proposed procedure and investigate its economic implications, differences in pile design between the interim and the proposed LRFD procedures were evaluated on the basis of independent data collected from more than 600 production steel H-piles driven in cohesive soils. This study concluded that the proposed LRFD procedure would not significantly increase the design and construction costs. The incorporation of pile setup into the LRFD procedure was found to provide additional economic benefits. Although the current Iowa DOT policy is to drive piles to the contract length, if a suitable pile termination procedure were used once the desired resistance was achieved, a general saving of 20% in pile length would be anticipated for both procedures. Although the research and findings presented in this paper are specific to a local area, these methods could be adopted nationally to increase the efficiency of bridge foundations for all states.

The allowable stress design (ASD) philosophy has been used for the design of pile foundations for decades. However, this approach does not ensure consistent reliability for pile design and installation. To improve the design of foundation piles and their reliability, FHWA mandated that all new bridges initiated after October 1, 2007, be designed using the load and resistance factor design (LRFD) procedure. For pile design, the AASHTO *LRFD Bridge Design Specifications* provided an LRFD framework and LRFD recommendations, which were developed using multiple pile load test databases that were collected throughout the United States and that represented general soil conditions, common design methods, and construction practices (*1*). Because of the potential conservatism of the AASHTO LRFD specifications and the anticipation of increased foundation costs, most state departments of transportation (DOTs) did not readily adopt the AASHTO LRFD recommendations, despite the FHWA-mandated deadline. According to a survey completed by AbdelSalam et al. in 2008, only 15 state DOTs (i.e., 31% of the 50 states) had fully adopted the geotechnical resistance factors specified in the AASHTO specifications; another 20 state DOTs (i.e., 40% of the states) were transitioning toward the LRFD approach (*2*). To ensure a smooth transition from ASD to LRFD, 12 state DOTs, including the Iowa DOT, adopted interim procedures, in which the LRFD resistance factors were calibrated to fit the ASD safety factor, until a regional LRFD procedure could be fully developed and verified.

This paper presents the verification of an LRFD approach developed for the design and construction of bridge steel H-piles in cohesive soils in Iowa; the approach was developed through a comprehensive research program (http://srg.cce.iastate.edu/lrfd/) funded by the Iowa Highway Research Board [see Roling et al. (*3*), AbdelSalam et al. (*4*), and Ng et al. (*5–7*)]. This LRFD approach, as well as the approaches developed for mixed and cohesionless soils, used a historical pile load test database (PILOT) compiled by Roling et al. (*3*), 10 full-scale pile load tests completed by Ng et al. (*5*), and a probability-based LRFD framework. In addition, an approach to quantify pile setup and integrate this phenomenon into LRFD has been formulated by Ng et al. (*5–7*).

This paper accounts for the effects of pile setup and provides a verification of the proposed design and construction control in cohesive soils through the use of field data obtained from production piles installed in 2009 and 2010 at various bridge projects in Iowa. The paper also presents the potential impacts on the foundation costs of changing the design practice from the current interim procedure to the proposed LRFD procedure. Despite the focus on one state, this outcome should be possible for many other DOTs if a comparable LRFD approach were developed.

INTERIM PROCEDURE

An interim procedure is currently used by the Iowa DOT as a short-term adaptation to LRFD. This procedure was developed with an assumption of foundation loads per the AASHTO Strength I load combination, in which dead (Q_D) and live (Q_L) loads are multiplied by load factors (γ) of 1.25 and 1.75, respectively (*1*). A dead load to live load ratio (Q_D/Q_L) of 1.5 is adopted for typical bridge span lengths of approximately 120 ft and the AASHTO HL93 design

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truck load. Pile resistance in the interim procedure is estimated by the Iowa Blue Book (IABB) method, which combines the α-method for cohesive materials and the Meyerhof semiempirical method for cohesionless materials (*8*) [see Dirks and Kam (*9*)]. Currently, a geotechnical resistance factor (φ) of 0.725 is being used for the IABB method, determined by fitting to an ASD safety factor of 2.0 for all soils types, as illustrated in the following equation:

$$\varphi = \frac{\gamma_D\left(\frac{Q_D}{Q_L}\right)+\gamma_L}{\left(1+\frac{Q_D}{Q_L}\right)\text{SF}} = \frac{1.25(1.5)+1.75}{(1+1.5)2.0} = 0.725 \tag{1}$$

where SF is the ASD safety factor.

Although a safety factor range from two to four has been reported by Hannigan et al. (*10*) and by Allen (*11*), a safety factor of 2.0 has been implemented in Iowa for the IABB method; the safety factor was developed on the basis of historical pile load tests in the late 1980s, when the AASHTO standard specifications had no guidelines for safety factors. If the applied factored load (γQ) is known for all appropriate strength–load combinations and soil information, such as a standard penetration test (SPT) *N*-value, then the number of piles and the contract pile length can be determined.

According to the current practice, every pile is driven to the contract length unless either early refusal (i.e., 160 blows per foot of pile penetration) is encountered or driving stresses exceed the allowable stress limit of 90% of the yield strength (F_y) (i.e., 45 ksi for Grade 50 steel). At the end of driving, pile resistance is ensured for the service load by means of a bearing graph (i.e., a plot of pile-driving resistances versus hammer blow counts) generated with the wave equation analysis program (WEAP); the bearing graph uses a safety factor of 2.2. The pile performance is accepted if the measured driving resistance, which is determined from the bearing graph that corresponds to the measured hammer blow count at the end of driving, exceeds or equals the plan design bearing (i.e., the total service load: $Q_D + Q_L$). In contrast, piles that do not satisfy the plan design bearing will be restruck, for a maximum of 12 hammer blows, approximately 24 h after the end of driving, and the performance criterion will be reevaluated. At this stage, the resistance of the piles in cohesive soils would have improved because of setup. Piles that fail to satisfy the performance criterion at the end of restrike will be extended in length and driven further into the ground until the target design bearing is achieved.

LRFD PROCEDURE

Development

To fully develop a regional LRFD procedure, comprehensive research was undertaken to determine suitable resistance factors that reflected local design and construction practices, as well as the regional soil conditions, by using the PILOT database, which contained historical load test data and data from 10 recently completed, extensively instrumented, full-scale pile load tests (*3, 5, 12*). The PILOT database contained data on 264 static pile load tests, conducted between 1966 and 1989, and was compiled electronically using Microsoft Office Access to establish quality-assured and usable static load test data on piles for use in LRFD calibrations through a quality assurance program. Of the tests in PILOT, 20 data sets on steel H-piles driven in cohesive soils included sufficient soil and pile information for geotechnical resistance calculations with the IABB method, and 12 data sets contained the necessary soil, pile, hammer, and driving information for WEAP analysis. The 10 recent full-scale field tests had been performed on steel H-piles (one 10×57 H-pile and nine 10×42 H-piles) at bridge construction sites throughout Iowa; five of the sites had a cohesive soil profile, for which the soil profile was defined as cohesive if soils along at least 70% of the pile embedment length were cohesive (*13*). The field tests involved detailed site characterization, the instrumentation of the test piles with strain gauges along the length, dynamic load tests with the Pile Driving Analyzer and subsequent case pile wave analysis program (CAPWAP) analyses, pile restrikes, and static load tests in accordance with the ASTM D1143 quick test procedure.

The field test results and the PILOT database both showed that steel H-piles embedded in cohesive soils exhibited increases in resistance after the end of driving that were attributable to setup of an average of 50% in 7 days. It was further observed that these piles exhibited a logarithmic setup trend, in which the pile resistance increased immediately and rapidly within a day of the end of driving and increased at a slower rate after the second day (*6*). A correlation study between pile setup resistance and the SPT *N*-value concluded that embedding piles in softer soil, characterized by undrained shear strength (S_u), led to a higher percentage increase in the pile resistance attributable to setup, and vice versa (*6*). The outcomes of this research led to a readily applicable pile setup resistance (R_{setup}) quantitative method given by Equation 2; the method incorporates an SPT *N*-value.

$$R_{\text{setup}} = \left[\frac{a \log\left(\frac{t}{t_{\text{EOD}}}\right)}{(N_a)^b}\right] R_{\text{EOD}} \tag{2}$$

where

- R_{setup} = pile setup resistance (kips);
- R_{EOD} = pile resistance at the end of driving, estimated with WEAP (kips);
- N_a = weighted average SPT *N*-value to cohesive soil thicknesses;
- a = empirical coefficient (0.215 for WEAP);
- b = empirical coefficient (0.148 for WEAP);
- t = time elapsed after end of driving (days) (typically taken as 7 days); and
- t_{EOD} = time at end of driving (taken as 0.000693 days, which is equal to 1 min).

The derivation and validation of Equation 2 were documented in Ng et al. (*5*), and the coefficient of determination (R^2) of Equation 2 was found to be .52. In the current AASHTO LRFD specifications, no recommendations are provided for pile setup estimation through empirical methods (*1*). Instead, dynamic restrike tests and static load tests are the only approaches suggested by AASHTO to quantify setup. Compared with the proposed empirical method, restrikes and load tests consume more resources during construction (*1*), and, thus, they are not routinely used in practice. The economic advantages attributable to the design of cost-effective bridge foundation solutions were recognized, and the proposed pile setup was incorporated into the LRFD procedure through a framework similar to that suggested by Yang and Liang (*14*), as in Equation 3:

$$\sum \gamma Q \le \varphi R = \varphi_{\text{EOD}} R_{\text{EOD}} + \varphi_{\text{setup}} R_{\text{setup}} \tag{3}$$

where

γ = AASHTO Strength I load factor;
Q = applied load;
R_{EOD} = pile resistance at the end of driving, determined from a bearing graph generated with WEAP (kips);
R_{setup} = pile setup resistance estimated with Equation 2 (kips);
φ_{EOD} = resistance factor for R_{EOD}; and
φ_{setup} = resistance factor for R_{setup}.

Each resistance component (R_{EOD} or R_{setup}) has its own uncertainties, which should be adequately reflected in the respective resistance factors when the required reliability for entire pile design process is achieved. The first-order second-moment method, given in Equation 4 and suggested by Barker et al. (*15*), was adopted to determine φ_{EOD} and φ_{setup}, as shown in Equation 5 (*9, 16*). The first-order second-moment approach was chosen because it involves minimal computation, particularly as compared with the Monte Carlo method, which provides only 10% to 20% higher resistance factors (*11*).

$$\varphi_{\text{EOD}} = \frac{\lambda_R\left(\frac{\gamma_D Q_D}{Q_L}+\gamma_L\right)\sqrt{\left[\frac{\left(1+\text{CV}_D^2+\text{CV}_L^2\right)}{\left(1+\text{CV}_R^2\right)}\right]}}{\left(\frac{\lambda_D Q_D}{Q_L}+\lambda_L\right)e^{\left\{\beta_T\sqrt{\ln\left[\left(1+\text{CV}_R^2\right)\left(1+\text{CV}_D^2+\text{CV}_L^2\right)\right]}\right\}}} \tag{4}$$

$$\varphi_{\text{setup}} = \frac{\lambda_{\text{setup}}\left[\frac{\gamma_D\left(\frac{Q_D}{Q_L}\right)+\gamma_L}{1+\left(\frac{Q_D}{Q_L}\right)}-\varphi_{\text{EOD}}\alpha\right]}{\frac{\left(\frac{\lambda_D\left(\frac{Q_D}{Q_L}\right)+\lambda_L}{1+\left(\frac{Q_D}{Q_L}\right)}\right)e^{\beta_T\sqrt{\ln\left[\left(1+\text{CV}_{R_{\text{EOD}}}^2+\text{CV}_{R_{\text{setup}}}^2\right)\left(1+\text{CV}_D^2+\text{CV}_L^2\right)\right]}}}{\sqrt{\frac{\left(1+\text{CV}_D^2+\text{CV}_L^2\right)}{\left(1+\text{CV}_{R_{\text{EOD}}}^2+\text{CV}_{R_{\text{setup}}}^2\right)}}}-\lambda_{\text{EOD}}\alpha} \tag{5}$$

where

λ_R = resistance bias factor of the ratio of the resistance as measured by the static load test to the estimated resistance (λ_{EOD} and λ_{setup} correspond to the end-of-driving and setup components, respectively);
CV_R = coefficient of variation of the ratio of the resistance as measured by the static load test to the estimated resistance ($\text{CV}_{R_{\text{EOD}}}$ and $\text{CV}_{R_{\text{setup}}}$ correspond to the end-of-driving and setup components, respectively);
γ_D and γ_L = dead load factor (1.25) and live load factor (1.75), respectively;
λ_D and λ_L = dead load bias (1.05) and live load bias (1.15), respectively;
CV_D and CV_L = coefficient of variation for dead load (0.1) and coefficient of variation for live load (0.2), respectively;
Q_D/Q_L = dead to live load ratio (2.0);
β_T = target reliability indices [2.33, which corresponds to a 1% probability of failure, and 3.00, which corresponds to a 0.1% probability of failure, as recommended by Paikowsky et al. to represent redundant and nonredundant pile groups, respectively (*17*)];
α = ratio of pile resistance at the end of driving to total load [$R_{\text{EDD}}/(Q_D + Q_L)$], where 1.60 was suggested as a median value between 1.5 (determined from field test results) and 1.8 (obtained from additional data sets on production steel H-piles, as presented in a later section); and
e = exponential constant.

Recommendations

Of the methods investigated for pile design through the use of a static method, the IABB method was found to be the most efficient, as shown by its having the highest efficiency factor (φ/λ) (*4, 18*). Thus, similarly to the interim procedure, the recommended LRFD procedure uses the IABB method during design to determine the contract pile length for a required pile resistance; WEAP is used as a pile construction control method. Through an evaluation of the data sets collected in PILOT and those obtained from the field tests, the probabilistic characteristics (i.e., λ and CV) were calculated for the IABB method and WEAP and are summarized in Table 1.

The resistance factors for the IABB method, which have no conjunction with any load test methods, were determined from Equation 4 to be 0.63 and 0.48 for $\beta_T = 2.33$ and $\beta_T = 3.00$, respectively. The calibrated resistance factor of 0.63 is approximately 13% lower than the resistance factor of 0.725 (see Equation 1) currently used in the interim procedure. Nonetheless, the calibrated resistance factor is higher than the comparable values recommended by AASHTO (e.g., 0.35 for the α-method and 0.40 for the λ-method) (*1*). Similarly, resistance factors for WEAP were calculated with Equation 4 for R_{EOD} and Equation 5 for R_{setup}. The probabilistic characteristics of R_{EOD} were determined from the distribution of the ratio of measurement-based pile resistances at the end of driving (estimated with CAPWAP) and R_{EOD} (estimated with WEAP). The probabilistic characteristics of R_{setup} were determined on the basis of the distribution of the ratio

TABLE 1 Regionally Calibrated LRFD Resistance Factors for IABB and WEAP

						$\beta_T = 2.33$		$\beta_T = 3.00$	
Stage	Method	Condition	N	λ_R	CV_R	φ	φ/λ	φ	φ/λ
Design	IABB	General	25	1.23	0.33	0.63	0.51	0.48	0.39
Construction	WEAP	EOD	17	0.93	0.16	0.65	0.71	0.55	0.59
		Setup	17	0.86	0.33	0.21	0.25	0.19	0.22

NOTE: EOD = end of driving; samples in N column from PILOT (20 for IABB method and 12 for WEAP) and five field tests in cohesive soils.

of the measured setup resistance and the estimated setup resistance through Equation 2, for which the measured setup resistance was the difference between the static load test capacity and R_{EOD} estimated with CAPWAP. The recommended φ_{EOD} of 0.65 is about 30% higher than the AASHTO resistance factor of 0.50 for WEAP, even without the setup component being incorporated.

Under the interim procedure, pile bearing in the field is verified by WEAP at the service level. Pile bearing under the LRFD framework is verified by WEAP at the end-of-driving strength level, without the need for restrikes, on the basis of a target nominal end-of-driving resistance ($R_{target\text{-}EOD}$), determined by substituting Equation 2 into Equation 3, such that

$$R_{target\text{-}EOD} = \frac{\sum \gamma Q}{\varphi_{EOD} + \varphi_{setup}\left[\frac{a \log\left(\frac{t}{t_{EOD}}\right)}{\left(N_a\right)^b}\right]} = \frac{\sum \gamma Q}{0.65 + \frac{0.181}{\left(N_a\right)^{0.148}}} = \frac{\sum \gamma Q}{\varphi_e} \tag{6}$$

An analysis of the denominator of Equation 6 reveals that when the effect of setup is included, the equivalent resistance factor (φ_e) falls from 0.81 for a weighted average SPT N-value (N_a) of 2 to 0.75 for an SPT N_a value of 50. The minimum φ_e of 0.75 is larger than the recommended φ of 0.63 for the IABB method, as given in Table 1, as well as the value of 0.725 used in the interim procedure. The anticipated benefits of the proposed LRFD procedure are as follows:

1. The target nominal pile driving resistance, determined through Equation 6, will be smaller than that determined with the IABB method ($\Sigma\gamma Q/0.63$) without accounting for setup;
2. If the target driving resistance at the end of driving were satisfied, piles could be driven shorter than the contract length determined with the IABB method;
3. Pile restrike about 24 h after the end of driving would not be needed as frequently because a smaller target pile driving resistance would be required; and
4. The economic advantages of pile setup could be realized while complying with the LRFD framework and ensuring a target reliability level.

As the previously mentioned LRFD procedure was developed on the basis of test piles, it was desirable to verify its application on recently designed and installed production piles. Additionally, it was important to highlight that the average embedded test pile length of about 55 ft, or 45 ft for those in PILOT, was less than the actual driven lengths of the production piles and ranged between 50 and 100 ft. Because of the differences in length, pile size, resistance distribution, and total pile resistance between the test piles and the production piles, and to avoid any bias originating from the use of shorter test piles, it was vital that the LRFD recommendations be verified on an independent set of production piles before they were implemented.

SUMMARY OF FIELD DATA

To verify the proposed LRFD procedure, independent data sets were obtained from production steel H-piles installed during bridge construction in 2009 and 2010; the data sets are summarized in Table 2. These data sets were obtained from 17 cohesive project sites located in 10 counties in Iowa. Information relating to the location of the production piles, the pile sizes, the embedded soils, the hammer used, the weighted average SPT N-value (N_a), and the plan pile lengths is included in Table 2. The 10 × 57 H-pile was the most common pile size; however, 10 × 42 H-piles and 12 × 53 H-piles were also used at some sites. The soil profile was generally glacial clay, and N_a values ranged between 11 and 51. All the piles were driven using diesel hammers. In Table 2, the plan pile length represents the contract pile length, which was determined by summing (*a*) the required pile embedment length, estimated with the IABB method, to resist the applied load per the recommended LRFD procedure with a φ factor of 0.63; (*b*) any prebore length at integral bridge abutments to overcome down drag; (*c*) the required pile extension into the footing (1 ft for a pier and 2 ft for an abutment); and (*d*) the minimum 1-ft cutoff allowance. The total plan pile length was rounded up to the nearest 5 ft. All production piles were assumed to be friction piles, for which the geotechnical shaft resistance was estimated to be, on average, about 84% of the total resistance estimated using the IABB method. After all the piles driven in rock were removed from consideration, a total of 604 production piles installed as part of 45 pile groups were selected for the verification study.

VERIFICATION

IABB Method Design

Given the pile and soil information in Table 2, nominal geotechnical resistances were estimated with the IABB method for all 604 production piles. After the recommended LRFD resistance factor of 0.63 (see Table 1) was applied to the nominal resistances, a histogram and a corresponding theoretical normal distribution were plotted for the ratio obtained between the factored geotechnical resistance and the corresponding factored loads, as shown in Figure 1. The mean value of 0.96 obtained for the distribution indicates that the factored geotechnical resistance estimated with the proposed LRFD procedure is approximately 4% less than that estimated with the interim procedure; in the interim procedure, the factored geotechnical resistances are the same as the factored loads (i.e., ratio = 1.0). The above observation was anticipated because the resistance factor fell from 0.725 in the interim procedure to 0.63 in the proposed LRFD procedure. However, a constant 13% reduction in factored resistances could not be realized because the nominal geotechnical resistances were reevaluated with the IABB method based on the available soil and pile information. Nevertheless, a mode of the ratio was observed between 0.88 and 0.92 in Figure 1, which implied that most data showed an 8% to 12% reduction in the factored resistance.

Despite the 13% reduction in the resistance factor, it is more appropriate to demonstrate the comparison in terms of the plan pile length; this comparison reflects the economic implications of switching from the interim procedure to the LRFD procedure. After the LRFD procedure was applied, plan pile lengths were revised according to the criteria described previously and were compared with the actual plan pile lengths, as listed in Table 2. Figure 2 shows a histogram and a theoretical normal distribution of the ratio of the plan pile lengths estimated with the LRFD procedure to those listed in Table 2. If the LRFD procedure had been implemented, the histogram suggests that 56% of the 604 production piles (i.e., 338 piles) would have required a longer plan pile length (i.e., the ratio was greater than 1.0) and that 44% of the 604 production piles (i.e., 266 piles) would have had a shorter or equal plan pile length (i.e., the

TABLE 2 Independent Field Data on Completed Production Steel H-Piles in Iowa

Iowa County and Identification Number	Pier or Abutment	Pile Size	Soil Description	Hammer	Average SPT N-value, N_a	Plan Pile Length (ft)
Lee-135	Pier 2	HP 10 × 57	Sandy GC	Delmag D19-42	31	45
	N. abutment	HP 10 × 57			26	60
Buena Vista-53	W. abutment	HP 10 × 42	Firm sandy GC over	Delmag D19-32	17	60
	E. abutment	HP 10 × 42	very firm glacial clay		22	60
	W. Pier 1	HP 12 × 53			22	60
	E. Pier 2	HP 12 × 53			20	60
Jasper-44	W. abutment	HP 10 × 57	Silty clay	Delmag D19-42	14	70 & 80
	Pier 2	HP 12 × 53	Stiff silty clay to very firm GC		22	70
	E. abutment	HP 10 × 57			15	75 & 80
Dickinson-35	E. abutment	HP 10 × 57	Sandy lean clay	Delmag D19-32	24	60
	W. abutment	HP 10 × 57	Firm sandy lean clay		16	60
	E. Pier	HP 12 × 53	Very firm GC		20	60
Plymouth-40	W. abutment	HP 10 × 57	Silty clay—GC	Delmag D19-32	14	80
	E. Pier	HP 10 × 57	Very firm GC		32	70
Wright-63	E. abutment	HP 10 × 42	GC	Delmag D16-32	14	45
	W. abutment	HP 10 × 42			11	45
Carroll-122	S. abutment	HP 10 × 42	Silty clay to firm GC	Delmag D46-13	16	55
	N. abutment	HP 10 × 42			16	55
Cedar-82	S. abutment	HP 10 × 57	Silty clay to firm GC	Delmag D19-42	16	80
	N. abutment	HP 10 × 57			18	80
	Pier 1	HP 10 × 57			18	55
	Pier 3	HP 10 × 57			19	55
	Pier 2	HP 10 × 57			19	60
Tama-114	Pier	HP 10 × 57	Silty clay to firm GC	APE D19-42	51	45
	N. abutment	HP 10 × 57			47	65
	S. abutment	HP 10 × 57			38	70
Tama-119	Pier	HP 10 × 57	Very firm GC	Delmag D19-42	28	45
	N. abutment	HP 10 × 57	Silty clay to very firm GC		27	60
	S. abutment	HP 10 × 57			27	60
Lee-130	Pier	HP 10 × 57	Firm sandy GC	Delmag D19-32	24	50
Lee-147	SBL S. abutment	HP 10 × 57	Stiff silty clay to very firm GC	APE D19-42	17	80
	NBL N. abutment	HP 10 × 57			17	80
	SBL Pier 1	HP 10 × 57	Firm GC		17	55
	NBL S. abutment	HP 10 × 57	Stiff silty clay		17	75
	NBL Pier 1	HP 10 × 57	Firm GC		19	55
Lee-148	S. abutment	HP 10 × 57	Silty clay	Kobe K-25	40	60
	Pier	HP 10 × 57	Very firm GC		40	40
Lee-157	E. abutment	HP 10 × 57	Stiff silty clay to firm GC	APE D19-42	17	70
	W. abutment	HP 10 × 57		Delmag D19-32	19	70
Lee-138	W. abutment	HP 10 × 57	Silty clay to GC	Delmag D19-32	15	70
	E. abutment	HP 10 × 57			15	70
	Pier 1	HP 12 × 53			17	45
Buena Vista-57	W. Pier	HP 10 × 57	GC to gravelly sand	Delmag D16-32	18	65
	W. abutment	HP 10 × 57	Silty clay to firm GC	Delmag D19-32	18	70
Johnson-285	Pier 1	HP 10 × 57	Sandy lean clay	Delmag D19-42	14	55

NOTE: N. = north; S. = south; E. = east; W. = west; abut. = abutment; NBL = northbound lane; SBL = southbound lane; GC = glacial clay.

ratio was less than or equal to 1.0). When all the actual plan pile lengths were accumulated, the interim procedure led to a value of 34,779 ft for all 604 piles; the LRFD procedure only increased the total plan pile length by 3.3% to 35,935 ft. Intuitively, a greater percentage increase in total pile length would have been expected from the 13% reduction in the resistance factor. The minimal increase is probably a result of the relatively high friction bearing near the tips of the piles, for which a short increase in pile length gives a large increase in bearing. Additionally, the theoretical normal distribution has a mean of 1.047 and a standard deviation of 0.128, thereby confirming the insignificant economic difference between the two procedures. Hence, it can be concluded that piles designed by the IABB method, based on the proposed LRFD procedure, will be economically comparable to the interim procedure, and the design reliability of the piles will be improved.

Construction Control with WEAP

During construction, the verification of production pile performance requires WEAP analyses and the generation of bearing graphs. The pile performance under the interim procedure was verified

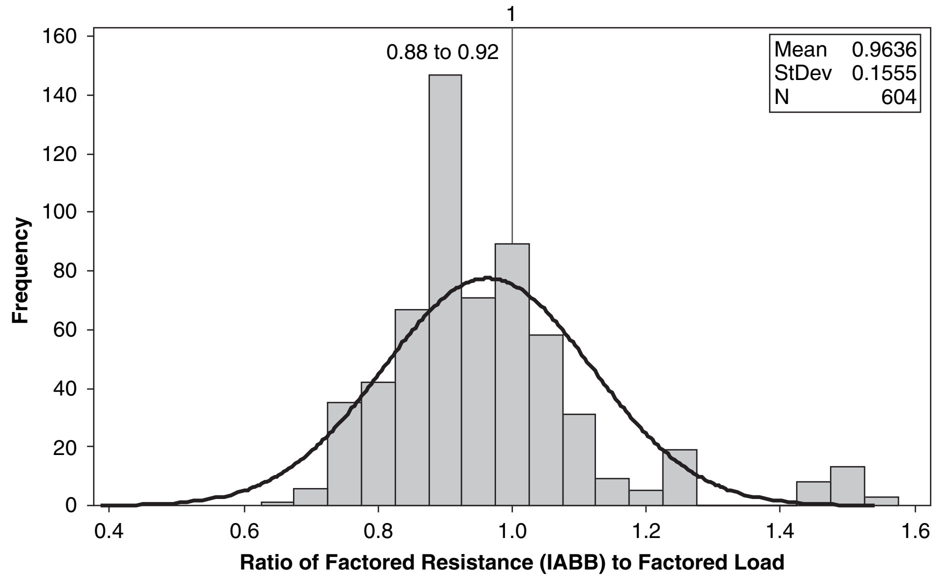

FIGURE 1 Ratio of factored geotechnical resistance, estimated with IABB, to factored applied load (StDev = standard deviation).

with the production pile data sets given in Table 2. The verification involved a comparison of the measured driving resistance at the end of driving, obtained from WEAP bearing graphs that were generated with a safety factor of 2.2, with the total service load (i.e., the plan design bearing). The performance is represented in Figure 3 by the short-dash normal distribution curve. The pile performance based on the LRFD procedure was verified by comparing the measured nominal driving resistance, determined from the nominal WEAP bearing graphs, with the target nominal driving resistance estimated using Equation 6. This comparison is plotted in Figure 3 and is represented by the long-dash normal distribution curve.

A comparison of the two normal distributions in Figure 3 illustrates that the LRFD procedure, which has a mean of 1.45, has a larger safety margin than the interim procedure, which has a mean of 1.33. The larger safety margin is also justified by the smaller area underneath the curve of the LRFD procedure in the region with ratios smaller than 1.0. These curves are different from a typical probability density function of the ratio of resistance and load (R/Q) used in resistance factor calibrations. This observation confirms that the LRFD procedure offers a better verification of pile performance and indicates that fewer production piles would fail to meet the target driving resistance, as alternatively illustrated in Table 3.

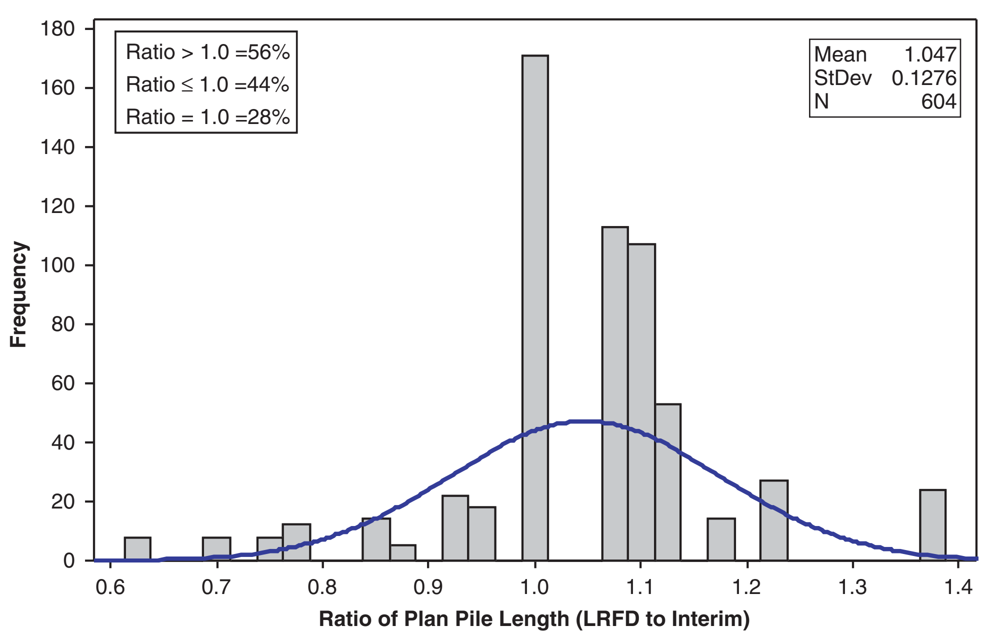

FIGURE 2 Comparison of plan pile lengths estimated with LRFD procedure and interim procedure.

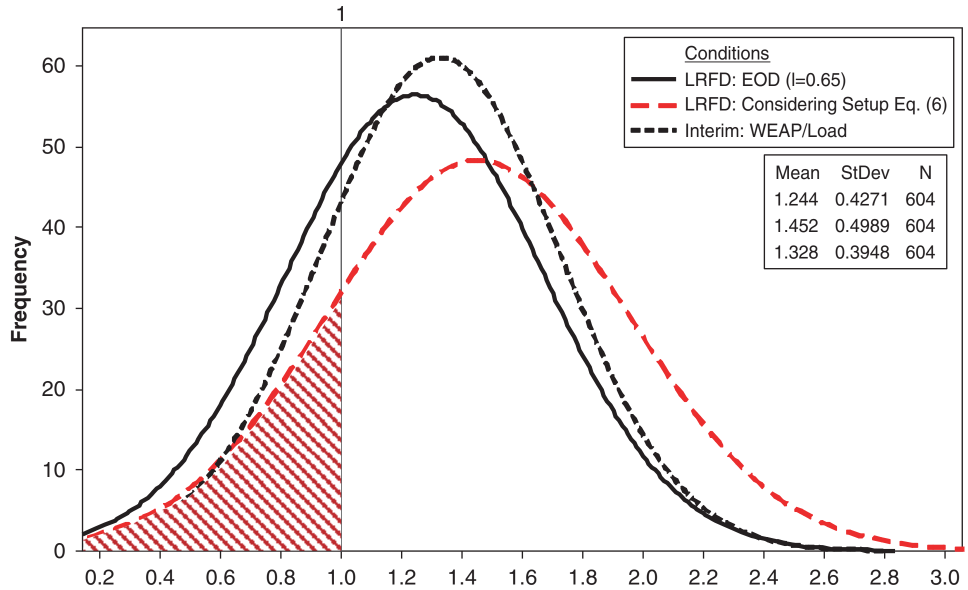

FIGURE 3 Ratio of driving resistance to target resistance or bearing [LRFD (EOD) = ratio of measured driving resistance at EOD to target driving resistance ($\gamma Q/\varphi_{EOD}$); LRFD (considering setup) = ratio of measured driving resistance at EOD to target driving resistance (Equation 6); Interim = ratio of driving resistance (considering safety factor = 2.2) to service load (plan design bearing)].

The results given in Table 3 reveal that, under the interim procedure, 101 production piles (16.7%) did not meet the target performance and required retap approximately 24 h after the end of driving, and that only 90 piles (14.9%) would require retap under the LRFD procedure. On the basis of experience, retap is used as a remedial measure, but the pile resistance at this stage would have increased as a result of setup. Typically, the successful retap of a single pile or selected piles is used as acceptable evidence in the field to accept all piles in the same group. Even if it were desired, it may not be feasible to retap all piles in the same pile group. Consequently, only 31 production piles (i.e., about one in three piles) were actually retapped, according to the field records. If the 24-h retap does not indicate sufficient driving resistance, then pile extension will be required. Table 3 shows that 10 piles (1.7%) required extension under the interim procedure and that only five piles (0.8%) would require extension if the LRFD procedure were followed. These comparisons conclude that the proposed LRFD procedure, with the consideration of pile setup using Equation 2, offers an economic advantage over the interim procedure.

Effect of Pile Setup

If pile setup is not considered, the target nominal driving resistance at the end of driving can be determined by dividing a factored load with the resistance factor of 0.65 (see Table 1). A comparison of the driving resistance measured at the end of driving with the target nominal driving resistance allows a normal distribution curve to be plotted, as represented by the solid line shown in Figure 3. Compared with the mean value of 1.45 for the distribution that considered pile setup (the long-dash line), this normal distribution curve, with a mean of 1.24, requires about a 17% higher target driving resistance. Additionally, a larger area is observed underneath the normal distribution curve in the region with ratios smaller than 1.0. This observation demonstrates that 224 (or 37%) of production piles will not meet the target driving resistance and will require retap, as illustrated in Table 3. The suggested incorporation of pile setup into the LRFD procedure can be seen to contribute significant economic benefits to bridge foundations.

Early Pile Termination

Under the LRFD procedure, the contract pile length was estimated with the IABB method, and the required pile penetration was determined with WEAP to ensure consistency in the installed pile resistance. As a result of the higher efficiency factor for WEAP (i.e., 0.71 and 0.25 for $\beta_T = 2.33$, as shown in Table 1), it was anticipated that a shorter pile length than the contract pile length would be sufficient during construction; this expectation was examined with a larger sample of production piles. Cost savings could be made if piles that satisfied the target driving resistance were terminated before the contract-specified length was reached. Figure 3 shows that most of the production piles, which were driven to their respective contract pile lengths under Iowa DOT's construction practice, exceeded their target driving resistances; this finding is substantiated by a mean of 1.45 and a standard deviation of 0.50 for the LRFD procedure (see Figure 3).

The savings that would result from the early termination of pile driving were investigated. Of the 604 data sets listed in Table 2, 35 production piles had detailed driving records; one such example—Production Pile 8 at Pier 1 in Cedar County, Iowa—is shown in Figure 4*a*. For this record, the nominal driving resistance for the LRFD procedure and the driving resistance, including a safety factor of 2.2, for the interim procedure were estimated with WEAP-generated bearing graphs, as shown in Figure 4*b*. With reference to the detailed driving resistance graph (such as the one shown in Figure 4*b*), the required pile embedment length that corresponds to

TABLE 3 Comparison Between Interim and Proposed LRFD Procedures

			Interim Procedure		Proposed LRFD Procedure		
Iowa County and Identification Number	Pier or Abutment	Total Piles	Piles Requiring Retap	Piles Requiring Extension	Piles Requiring Retap (EOD)	Piles Requiring Retap (with setup)	Piles Requiring Extension
Lee-135	Pier 2	29	0	0	0	0	0
	N. abutment	12	0	0	0	0	0
Buena Vista-53	W. abutment	7	0	0	0	0	0
	E. abutment	7	0	0	0	0	0
	W. Pier 1	13	0	0	0	0	0
	E. Pier 2	13	0	0	0	0	0
Jasper-44	W. abutment	7	7	5	7	7	5
	Pier 2	14	0	0	14	0	0
	E. abutment	7	0	0	7	0	0
Dickinson-35	E. abutment	6	0	0	0	0	0
	W. abutment	6	0	0	0	0	0
	E. Pier	8	0	0	0	0	0
Plymouth-40	W. abutment	6	0	0	0	0	0
	E. Pier	12	0	0	0	0	0
Wright-63	E. abutment	5	0	0	0	0	0
	W. abutment	5	0	0	0	0	0
Carroll-122	S. abutment	7	0	0	0	0	0
	N. abutment	7	0	0	0	0	0
Cedar-82	S. abutment	5	0	0	5	5	0
	N. abutment	5	4	0	5	5	0
	Pier 1	22	5	0	22	6	0
	Pier 3	22	11	0	22	12	0
	Pier 2	22	13	0	22	15	0
Tama-114	Pier	27	0	0	17	11	0
	N. abutment	12	11	0	11	11	0
	S. abutment	13	9	1	11	5	0
Tama-119	Pier	27	13	0	20	4	0
	N. abutment	14	14	0	2	0	0
	S. abutment	13	0	0	3	0	0
Lee-130	Pier	36	0	0	0	0	0
Lee-147	SBL S. abutment	8	0	0	4	0	0
	NBL N. abutment	8	0	0	8	0	0
	SBL Pier 1	24	0	0	0	0	0
	NBL S. abutment	8	0	0	6	0	0
	NBL Pier 1	24	0	0	1	0	0
Lee-148	S. abutment	12	0	0	0	0	0
	Pier	26	0	0	0	0	0
Lee-157	E. abutment	11	0	0	7	0	0
	W. abutment	11	0	0	8	0	0
Lee-138	W. abutment	7	7	4	7	6	0
	E. abutment	7	0	0	0	0	0
	Pier 1	27	7	0	9	3	0
Buena Vista-57	W. Pier	12	0	0	2	0	0
	W. abutment	6	0	0	0	0	0
Johnson-285	Pier 1	24	0	0	4	0	0
Total (percent of total piles)		604	101 (16.7%)	10 (1.7%)	224 (37%)	90 (14.9%)	5 (0.8%)

the target nominal driving resistance, calculated with Equation 6, for the LRFD procedure can be determined, as can the driving resistance for the interim procedure. For instance, Figure 4*b* illustrates that the required embedded length that corresponds to the target nominal driving resistance of 171 kips was determined to be 47.8 ft, which is smaller than the actual embedded length of 52.5 ft. Figure 5 shows the comparison between 35 required and actual embedded pile lengths for both procedures. This figure reveals that most required embedded pile lengths are smaller than the actual lengths, with mean ratios of 0.79 and 0.78 for the interim and LRFD procedures, respectively.

In terms of the total actual embedded length of 1,802 ft, the LRFD procedure will save about 20%; the interim procedure could save about 21%. This evaluation concludes that a general 20% saving in the pile embedment lengths could result from the use of the recommended LRFD design and construction methods with the

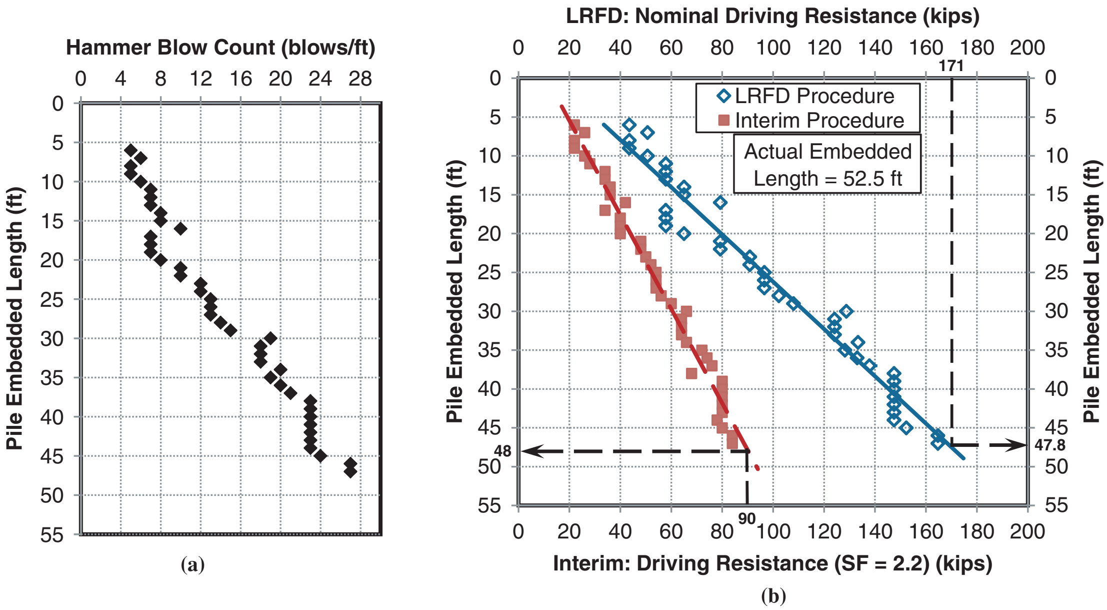

FIGURE 4 Driving details of Production Pile 8 at Pier 1 in Cedar County, Iowa: (*a*) detailed pile-driving record and (*b*) detailed pile-driving resistance graph (SF = safety factor).

incorporation of setup; additional cost savings in terms of driving and labor costs will also be realized.

CONCLUSIONS

To overcome the potential conservatism of the AASHTO LRFD recommendations and the consequent increase in foundation costs, some state DOTs, including the Iowa DOT, have adopted interim procedures that were developed to match the previously used ASD safety factors. A comprehensive research program was undertaken in Iowa to develop a suitable regional LRFD procedure for the design and construction of bridge foundations (http://srg.cce.iastate.edu/lrfd/). This program was undertaken because a regional database of driven pile records could lead to larger resistance factors than the general factors given in the *AASHTO LRFD Bridge Design Specifications;* these resistance factors could lead to significant cost reductions in driven pile foundations.

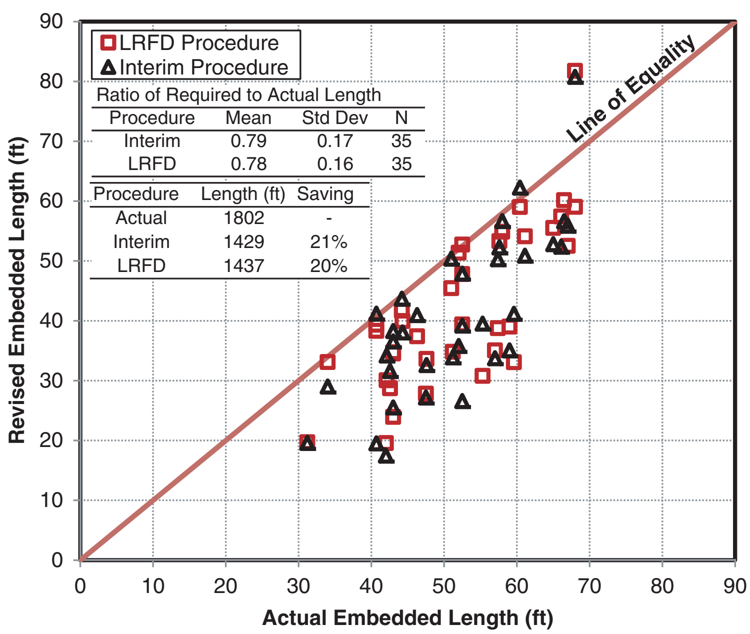

FIGURE 5 Comparison of required embedded pile lengths for interim and LRFD procedures and actual embedded pile lengths.

This paper primarily examined the potential economic consequences of switching the design and construction of bridge foundations from the interim procedure to a proposed LRFD procedure that takes advantage of pile setup with sufficient conservatism. This study was completed with data collected from 604 production steel H-piles driven in cohesive soils in 2009 and 2010, and the following conclusions have been drawn:

1. The reliability analysis for the IABB approach, conducted with the first-order second-moment method, resulted in a resistance factor of 0.63, which was lower than the factor of 0.725 used in the interim procedure. Nonetheless, the resistance factor remained higher than the comparable values recommended by AASHTO. This verification study found that the factored geotechnical resistance estimated with the proposed LRFD procedure was about 4% less than that estimated with the interim procedure. In terms of the total plan pile length estimated for all 604 piles in cohesive soils, the LRFD procedure only increased the length by about 3.3%. This insignificant difference indicates that pile design using the IABB method, based on the proposed LRFD procedure, is economically comparable to the current interim procedure.
2. The regionally calibrated resistance factor of 0.65 is about 30% higher than the AASHTO resistance factor of 0.50 for WEAP, even without the incorporation of the setup component. For construction control that uses WEAP and considers pile setup, the results show that the LRFD procedure provides a larger safety margin against the factored applied load and a better means of controlling pile performance. In total, 85.1% of the production piles driven in cohesive soils under the LRFD procedure would meet the target driving resistance and would not require retap, compared with 83.3% of the production piles for the interim procedure. Only a negligible number of production piles (0.8%) designed with the LRFD procedure would require extension in the field. This demonstrates that the LRFD procedure has a slight economic advantage over the interim procedure.
3. The incorporation of pile setup in cohesive soils reduces the target driving resistance by about 17%. When pile setup is not included, a larger percentage of piles (37%) will not meet the target driving resistance and require retap, compared with 14.9% of production piles when pile setup is taken into account. This shows that the incorporation of pile setup into the LRFD procedure provides additional economic benefits.
4. If a suitable early pile termination procedure is implemented when the desired pile resistance is achieved, it is estimated that both the interim and LRFD procedures would generally save 20% in pile lengths.
5. Changing from the interim procedure to the proposed LRFD procedure would not significantly increase pile design and construction costs. In fact, the proposed LRFD procedure provides economic advantages to the bridge foundations.

Although the investigation presented in this paper is specific to Iowa, comparable outcomes are likely in other states.

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