BRIDGE ENGINEERING CENTER

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RESEARCH PROJECT TITLE

Development of LRFD Procedures for Bridge Pile Foundations in Iowa Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup

SPONSORS

Iowa Highway Research Board
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Iowa Department of Transportation
(InTrans Project 08-313)

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The Bridge Engineering Center (BEC) is part of the Institute for Transportation (InTrans) at Iowa State University. The mission of the BEC is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

IOWA STATE UNIVERSITY
Institute for Transportation

Development of LRFD Procedures for Bridge Pile Foundations in Iowa

Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup

tech transfer summary

This project has developed regional LRFD recommendations for driven piles so that bridge foundations can be designed and constructed with uniform reliability and cost effectiveness.

Background

The Federal Highway Administration (FHWA) mandated utilizing the Load and Resistance Factor Design (LRFD) approach for all new bridges initiated in the US after October 1, 2007. As a result, there has been a progressive move among state departments of transportation (DOTs) toward an increased use of LRFD in geotechnical design practices.

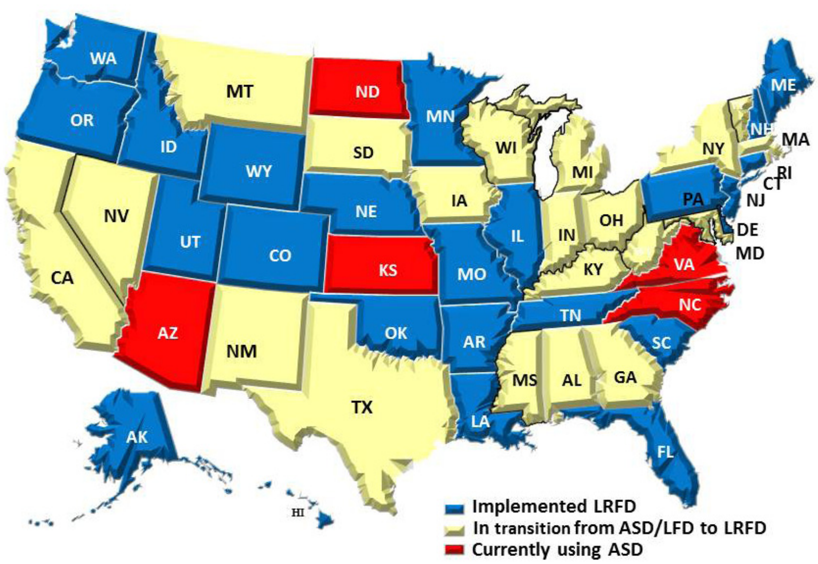
Objectives

The main goal of this project was to develop regionally-calibrated LRFD resistance factors for bridge pile foundations in Iowa based on reliability theory, focusing on the strength limit states, and incorporating the construction control aspects and soil setup into the design process.

Research Description and Scope

The calibration framework was selected to follow the guidelines provided by the American Association of State Highway and Transportation Officials (AASHTO), taking local practices into consideration.

The resistance factors were developed for general and in-house static analysis methods used for the design of pile foundations, as well as for dynamic analysis methods and dynamic formulas used for construction control.



Extent of LRFD implementation for bridge foundations from survey in 2008 (where ASD/LFD=allowable stress design/load factor design)

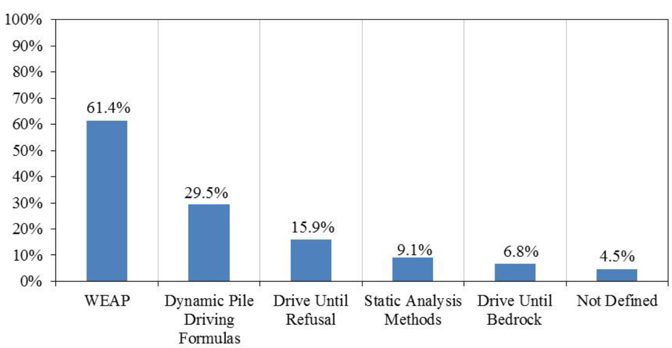
To ensure an understanding of the current bridge foundation design and construction practices, national and local surveys of state DOTs and county engineers were conducted and results were assimilated. Thirty-one responses were collected and the outcomes were integrated into the design.

The study developed the LRFD resistance factors using a recently developed pile load test database (known as PILOT), as well as data from 10 full-scale instrumented pile load tests that were conducted in different soil types in Iowa as part of this project.

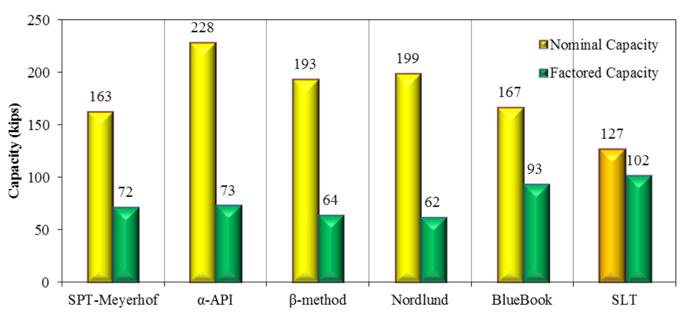
Following a summary of the selected calibration framework to better understand the most suitable calibration approach, the final report presents the preliminary values of the regionally-calibrated LRFD resistance factors for static methods, dynamic methods, and dynamic formulas. These factors were established using only the data from PILOT.

The performance of the preliminary resistance factors was evaluated by means of the full-scale instrumented pile load test data. Verification and adjustments made to the preliminary values are documented in the report.

Following the LRFD framework, the construction control aspects and pile setup were integrated in the design, which is presented in a separate chapter of the report. Another chapter provides the final LRFD recommendations for pile design in the form of design/construction tables and charts.



Criteria determining pile driving termination from the survey



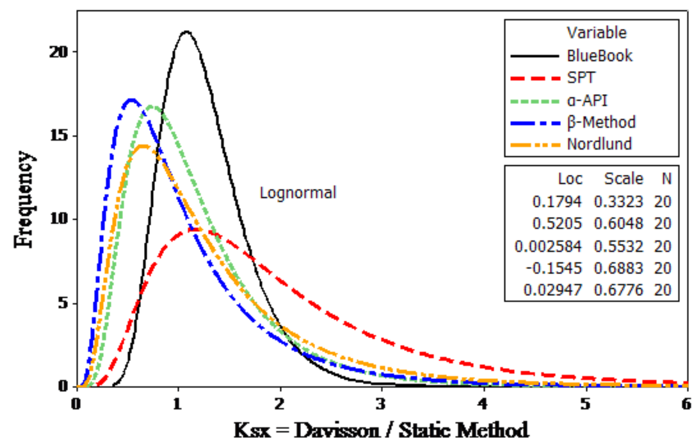
Nominal and Factored pile design capacities obtained for different static methods and static load test (SLT) for a pile embedded in sand

Key Findings

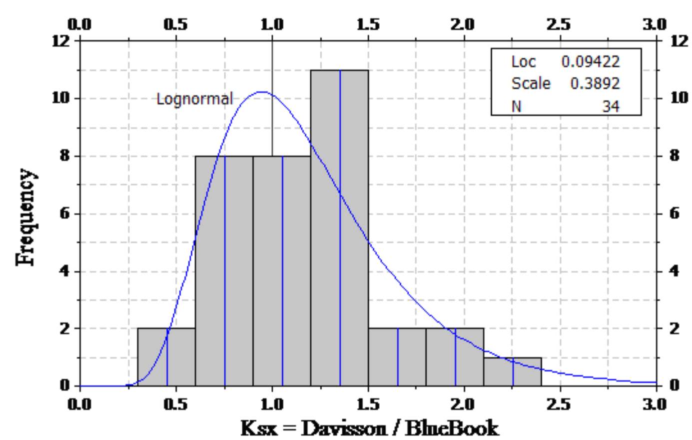
In this research, the LRFD resistance factors calibration framework was selected to follow the 2008 AASHTO and National Cooperative Highway Research Program (NCHRP)-507 guidelines, taking into consideration the current local practices in Iowa. The resistance factors were developed for general and in-house design and construction methods.

Compared with the current AASHTO LRFD specifications and the NCHRP-507 guidelines, a substantial increase in the regionally-calibrated resistance factors was noticed. Comprehensive tables and figures are provided in the report, as well as summaries of the major outcomes of the research for static analysis methods, dynamic analysis methods, and dynamic formulas.

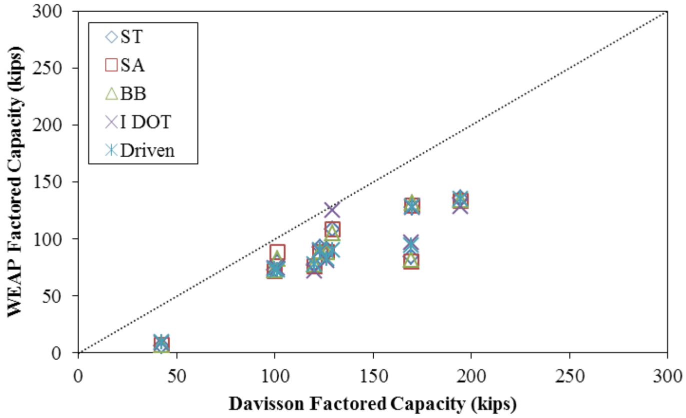
Some of the summary results are included in the figures in this tech transfer summary.



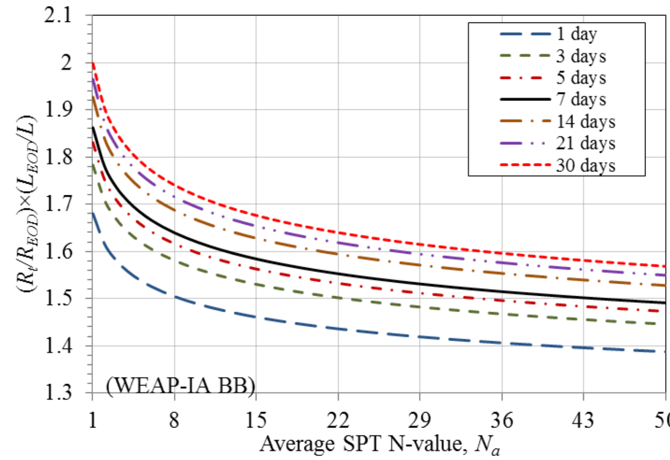
Summary of the lognormally-distributed PDFs of the resistance bias (K_{sx}) for the 20 cases of steel H-piles designed in clay using different static analysis methods



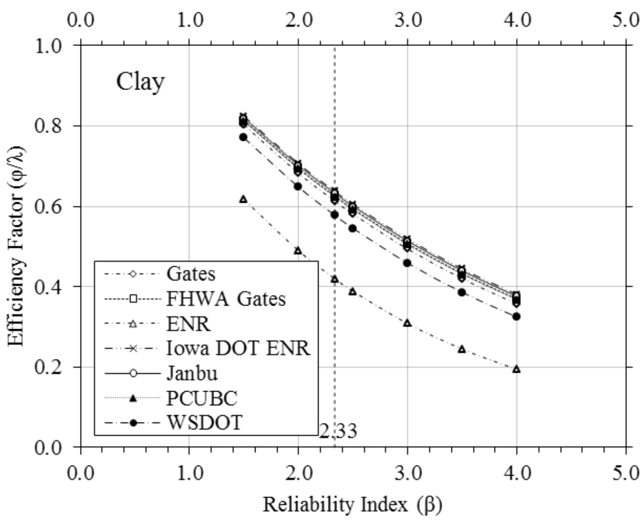
Histogram and frequency distribution of the resistance bias (K_{sx}) for 34 cases of steel H-piles designed in sand using the Iowa Blue Book method



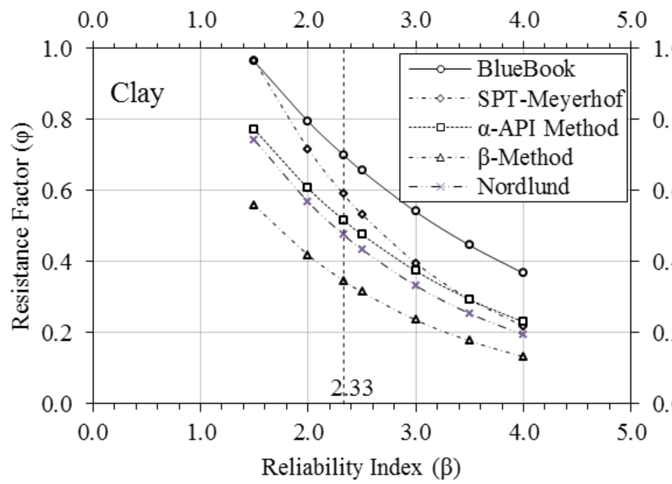
Factored measured and calculated capacities for the 10 field tested piles using Davisson's criterion versus WEAP



Soil setup design chart for WEAP



Efficiency factors for dynamic formulas corresponding to different reliability index (β) in sand



Resistance factors for static methods corresponding to different reliability index (β) in clay soil

Recommendations

The Iowa "Blue Book" (Dirks and Kam 1994) method is recommended for pile design to satisfy the LRFD requirements, because it provides the most efficient design and reflects design practices in Iowa. Among the different dynamic formulas, the Iowa DOT Engineering News Record (ENR) formula is recommended due to its efficiency and the common use in current practice.

To maintain a consistency between pile design and construction, the Iowa Blue Book soil input procedure is selected for Wave Equation Analysis Program (WEAP) analysis. In addition, other pile construction control methods (Pile Driving Analyzer/PDA with Case Pile Wave Analysis Program/CAPWAP and static load test) were included.

Note that the recommended resistance factors were developed for steel H-piles. Hence, these resistance factors shall be thoughtfully used for other driven pile types.

Under the design stage, an appropriate resistance factor will be selected depending on the type of soil profile in which production steel H-piles will be installed and the construction control method that will be employed during construction to verify the target pile performance.

Under the construction stage, either the Iowa DOT ENR formula or WEAP with the option of restrikes is recommended as a construction control method to establish production pile driving criteria. In addition, static pile load test or PDA with subsequent CAPWAP analysis with the option of restrike can be included to enhance the construction control procedure.

Appropriate resistance factors shall be selected, depending on the soil profile and the construction control procedure. The recommended resistance factors are summarized in the report. The complete design guide and track examples to demonstrate the application of the proposed LRFD procedure are being developed for the Volume IV report.

Recommended resistance factors for design and construction control

<table>
<tr><th rowspan="3">Stage</th><th colspan="5">Construction control (field verification)</th><th colspan="5">Resistance factor (φ)[a]</th></tr>
<tr><th colspan="2">Driving Criteria Basis</th><th rowspan="2">PDA/ CAPWAP</th><th rowspan="2">Restrike Test after EOD</th><th rowspan="2">Static Pile Load Test</th><th colspan="3">Cohesive</th><th>Mixed</th><th>Non-cohesive</th></tr>
<tr><th>Iowa DOT ENR</th><th>WEAP</th><th>φ</th><th>φ_{EOD}</th><th>φ_{setup}</th><th>φ</th><th>φ</th></tr>
<tr><td rowspan="4">Design[c]</td><td>Yes</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0.60[l]</td><td>-</td><td>-</td><td>0.60</td><td>0.50[l]</td></tr>
<tr><td rowspan="3">No</td><td rowspan="3">Yes[e]</td><td>-</td><td>-</td><td>-</td><td>0.65[k]</td><td>-</td><td>-</td><td>0.65[j k]</td><td>0.55[k]</td></tr>
<tr><td rowspan="2">Yes</td><td>-</td><td>-</td><td>0.70[g]</td><td>-</td><td>-</td><td>0.70[h]</td><td rowspan="2">0.60[i]</td></tr>
<tr><td>Yes</td><td>-</td><td>0.80</td><td>-</td><td>-</td><td>0.70</td></tr>
<tr><td rowspan="6">Construction[d]</td><td>Yes</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0.55[p]</td><td>-</td><td>-</td><td>0.55[p]</td><td>0.50[p]</td></tr>
<tr><td rowspan="5">No</td><td rowspan="5">Yes[e q]</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0.65</td><td>0.20</td><td rowspan="2">0.65[m o]</td><td rowspan="2">0.55</td></tr>
<tr><td>-</td><td>Yes</td><td>-</td><td>0.70</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Yes[f]</td><td>-</td><td>-</td><td>-</td><td>0.75</td><td>0.40</td><td rowspan="2">0.70[o]</td><td rowspan="2">0.70[i]</td></tr>
<tr><td>Yes</td><td>-</td><td>0.80</td><td>-</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>Yes</td><td>0.80[n]</td><td>-</td><td>-</td><td>0.80[n]</td><td>0.80[n]</td></tr>
</table>

a Provide a minimum of five piles per redundant pile group
b Use the Iowa Blue Book to estimate the theoretical nominal pile resistance
c Use the applicable resistance factor to estimate factored resistance using the Iowa Blue Book method during design
d Use the applicable resistance factor to determine the driving criteria required to achieve the target nominal driving resistance
e Use the Iowa Blue Book soil input procedure in WEAP analysis
f Use signal matching to estimate total resistance
g Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control
h Similar value of 0.70 for clay was recommended for mixed soil rather than 0.80
i Assumed for both conditions due to the fact that pile setup does not occur in sand
j 0.65 was adjusted from 0.64 to minimize design discrepancy for piles in clay and mixed soils
k Improved resistance factors calibrated based on modified First Order Second Moment (FOSM) and rounded to nearest 0.05 can be used (i.e., 0.70 for clay, 0.65 for mixed soil, and 0.60 for sand)
l 0.60 was adjusted from 0.63 for clay and 0.50 was adjusted from 0.55 for sand so that the recommended resistance factors are smaller than those considering either WEAP or CAPWAP as a construction control method
m 0.65 was adjusted from 0.80 to eliminate the effect of some pile setup in mixed site
n 0.80 was adopted from AASHTO specifications (2010)
o 0.65 for WEAP and 0.70 for CAPWAP were assumed as limited samples were available for resistance factors calibration
p Resistance factor shall be reduced to 0.35 for redundant pile groups if Iowa DOT ENR formula is used in construction control of timber piles
q Resistance factor shall be reduced to 0.40 for redundant pile groups if WEAP is used in construction control of timber piles

Implementation Benefits

The following notable benefits to the bridge foundation design were attained in this phase of the project:

- Comprehensive design tables and charts to facilitate the implementation of the LRFD approach, ensuring uniform reliability and consistency in the design and construction processes of bridge pile foundations
- A substantial gain in the factored capacity compared to the 2008 AASHTO LRFD recommendations
- Contributions to the existing knowledge, thereby advancing the foundation design and construction practices in Iowa and the nation

Future Research

1. LRFD calibration for serviceability limit state, including vertical and horizontal displacements
2. Calibration for lateral strength and serviceability limit states
3. Accounting for extreme loads
4. Accounting for soil relaxation aspects
5. Increasing the database to include more drivability information, especially in clay soils
6. Conducting the calibration for timber piles when necessary information is available

References

Dirks, Kermit and Patrick Kam. *Foundation Soils Information Chart, Pile Foundation ("Blue Book")*. Soils Survey Section, Highway Division, Iowa DOT. Ames, IA. 1994.