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RESEARCH PROJECT TITLE

Development of LRFD Procedures for Bridge Pile Foundations in Iowa
Volume II: Field Testing of Steel Piles in Clay, Sand, and Mixed Soils and Data Analysis

SPONSORS

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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.

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IOWA STATE UNIVERSITY
Institute for Transportation

Development of LRFD Procedures for Bridge Pile Foundations in Iowa

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tech transfer summary

Variability in soil characteristics, complexity in soil-pile interaction, and difficulty in predicting pile resistance and driving stresses pose many challenges for foundation element design.

Objectives

This project had the following objectives: 1) Install and load test piles in the field; 2) Collect complete data including driving data; 3) Improve design of piles in accordance with Load and Resistance Factor Design (LRFD) specifications; 4) Develop a suitable dynamic analysis method for pile design; and 5) Disseminate research outcomes to bridge designers in Iowa and elsewhere.

Background

Since the mid-1980s, the LRFD method has been progressively developed to ensure a better and more-uniform reliability of bridge design in the US. The Federal Highway Administration (FHWA) has mandated that all new bridges initiated after October 1, 2007 will follow the LRFD design approach (FHWA 2000).

Because of high variability in soil characteristics, complexity in soil-pile interaction, and difficulty in predicting a rational pile resistance and driving stresses, design in foundation elements pose more challenges than the superstructure elements. To improve the economy of foundation design, the American Association of State Highway and Transportation Officials (AASHTO) has recommended that higher resistance factors be used in the LRFD design method at a specific region where research has been conducted and/or past foundation data is available for validating the changes (AASHTO 2007).



Field test site and completed static load test frame (inset)

In response to this recommendation, the Iowa Highway Research Board (IHRB) sponsored a research project, TR-573, in July 2007 to develop resistance factors for pile design using the Pile Load Test (PILOT) database from past projects completed by the Iowa Department of Transportation (DOT) from 1966 to the late 1980s. The details of the PILOT database are described in the TR-573 LRFD Report Volume I.

Although the PILOT database enables the development of the LRFD resistance factors for static methods, dynamic formulas, and the Wave Equation Analysis Program (WEAP) from the static load test data, it is not inclusive of all soil profiles in Iowa and provides only a limited amount of reliable data.



In situ investigations (SPT)



Laboratory soil tests (consolidation test)

Furthermore, the PILOT database does not include Pile Driving Analyzer (PDA) driving data, which should be used to provide a reliable construction control method, predict pile damage resulting from pile driving, determine the contribution of shaft friction and end bearing to pile resistance, and develop the LRFD resistance factors for the PDA and Case Pile Wave Analysis Program (CAPWAP).

Research Description

Two add-on research projects (TR-583 and TR-584) were proposed and included to conduct 10 field tests and obtain a complete set of data. The commonly-used steel H-piles in Iowa for bridge foundations were chosen in the 10 field tests that cover all five geological regions in Iowa.

These field tests involved detailed site characterization using both in situ subsurface investigations, which consisted of Standard Penetration Tests (SPTs), Piezocone Penetration Tests (CPTs) with pore water pressure dissipation measurements, Borehole Shear Tests (BSTs), and modified Borehole Shear Tests (mBSTs), as well as laboratory soil classification and consolidation tests.

In addition, push-in pressure cells were installed within 24 in. (610 mm) from designated pile flanges to measure the changes in lateral earth pressure and pore water pressure during pile driving, re-strikes and static load tests (SLTs). Prior to pile driving, the test piles were instrumented with strain gauges along the embedded pile length for axial strain measurements. In addition, two PDA strain transducers and two accelerometers were installed 30 in. (750 mm) below the pile head to record the pile strains and accelerations during driving and re-strikes, which were converted into force and velocity records for CAPWAP analyses. During pile driving and re-strikes, pile driving resistances (hammer blow counts) were recorded for WEAP analyses. After completing all the re-strikes on the test piles, vertical SLTs were performed on test piles following the “Quick Test” procedure of ASTM D1143.



Pile instrumentation (left) and its protection (right)

The field tests provided the following data: 1) detailed soil profiles with appropriate soil parameters; 2) lateral earth and pore water pressure measurements from the push-in pressure cells; 3) strain and acceleration measurements using the PDA during driving, at end of driving (EOD), and at the beginning of re-strikes (BOR); and 4) vertical static load test data.

Interpretation and analysis of data was performed using static analysis methods, dynamic analysis methods, and dynamic formulas.

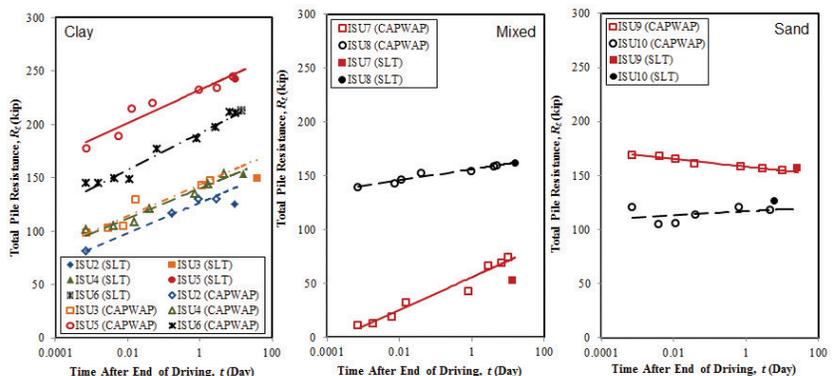
Key Findings

The extensive experimental research studies generated important data for concurrent analytical and computational investigations. Results from re-strikes and static load tests were compared. The SLT-measured load displacements were compared with the simulated results obtained using TZ-mBST model. The relationship between PC measurements and estimated pile responses was assessed. The variation in pile responses was evaluated with respect to the time elapsed after pile installation and was correlated with the surrounding soil properties. Two analytical pile setup quantification methods were developed and validated. A new calibration procedure was developed to incorporate pile setup into LRFD. The results of this research project led to the following conclusions.

1. Total pile resistance is obtained predominantly from shaft resistance while end bearing ranges between 2 and 28 percent of the total resistance.
2. Shaft resistance is higher at a stiffer soil layer, represented with a relatively large uncorrected SPT N-value.
3. The TZ-mBST model has proven to provide a better match of the measured SLT load-displacement relationship when compared to the TZ-CPT model.
4. The continuous logarithmic dissipation of pore water pressure with time explains the observed pile setup trend. Alternatively, for the cohesionless soil layer, the immediate and complete pore water dissipation before EOD explains the minimal variation in pile resistance over time.
5. Comparison of the measured pile driving resistances concludes that setup occurs in piles embedded in clay and mixed soil profiles but not in the sand profile. The re-strike and load test measurements show that the increase in total pile resistance has a general logarithmic trend with respect to time for clay and mixed soil profiles. Furthermore, the field test results indicate that pile resistance increases immediately and significantly after pile installation and, thus, the performance of re-strikes within a day after EOD is reasonably recommended. The CAPWAP results in the clay profile reveal that both shaft resistance and end bearing increase logarithmically with time, and pile setup is contributed to predominantly from the shaft resistance and minimally from the end bearing. Unlike the clay profile, test pile ISU8 in the mixed soil profile experienced a contrasting observation.
6. The experimental results confirmed that the amount of increase in shaft resistance at a given time was dependent on the combined effects of: 1) soil permeability, which was measured directly using the coefficient of consolidation or indirectly using the SPT N-values; 2) soil compressibility, which was measured using the plasticity index (PI) values; and 3) corresponding thicknesses of all the cohesive layers along the embedded pile length. The quantitative correlation studies specifically revealed that the increases in total pile capacity and shaft resistance of a pile embedded in a cohesive clay soil were directly proportional to C_v or C_h and were inversely proportional to SPT N-values and PI values greater than 12 percent. However, they were directly proportional to PI values less than 12 percent for a pile embedded in a sandy cohesive soil. Alternatively, the increase in the end bearing component showed no significant correlations to either SPT N-values or C_h values, but was directly proportional to the C_v and inversely proportional to the PI values.



Pile installation with restrikes and PDA (inset)

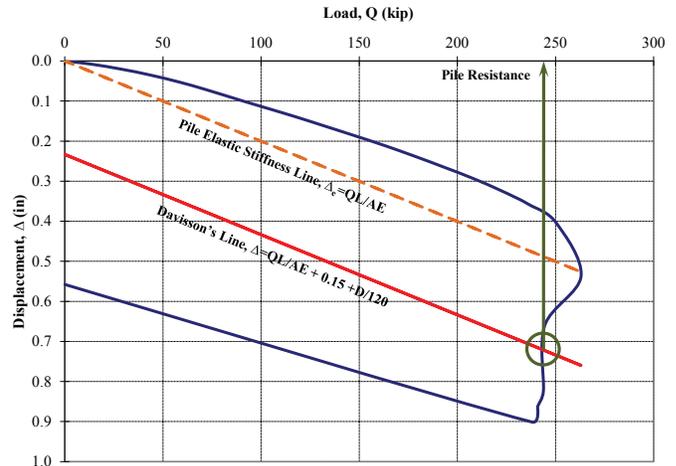


Measured pile setup using PDA and CAPWAP

7. Based on the field test results and the successful correlation studies, two analytical quantification methods were established to estimate the pile setup rate in a clay profile using the influential soil properties measured from the commonly-used SPT and CPT and using the dynamic analysis methods (WEAP and CAPWAP). The first method involves both SPT and CPT, while the second method involves only SPT. The quantification of pile setup rate in terms of soil properties avoids the inconvenient re-strikes and allows the estimation of pile resistance at any time.

8. Using 12 records from the PILOT database along with the five field tests, the confidence of the proposed pile setup methods were validated at various confidence levels. The maximum error falls between -17.2 and 1.9 percent, based on the SPT-based setup method when used in conjunction with WEAP at the 98 percent confidence interval. Generally, the range of the errors is less for pile setup methods when used in conjunction with CAPWAP than those with WEAP.

9. Recognizing the difference in uncertainties associated with the estimations of initial pile resistance at EOD and pile setup resistance, representing different COV values of 0.181 and 0.330 for WEAP, separate resistance factors are calculated for both initial pile resistance and setup resistance to ensure the reliability theory-based LRFD framework is adequately followed. Considering the AASHTO (2007) strength I load combination for axially loaded piles, the resistance factor for pile setup (ϕ_{setup}) is calculated, derived based on FOSM, and explicitly described by Ng (2011). For a typical α value of 1.6, Q_D/Q_L ratio of 2.0, and ϕ_{EOD} of 0.66 for the $\beta_T=2.33$, the ϕ_{setup} value of 0.21 can be conservatively recommended.



Typical load-displacement curve and Davisson's criteria (ISU5)



Completed static load test frame

Implementation Benefits

The completion of data analysis and interpretation will:

- 1) lay the foundation for developing a comprehensive database that can be populated at a reduced cost;
- 2) establish LRFD specifications for designing steel H-piles using static methods, dynamic analysis methods, and dynamic formulas;
- 3) develop a reliable construction control method using the dynamic analysis methods and dynamic formulas; and
- 4) quantify increase in pile capacities resulting from setup as a function of time.

References

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Ng, K. W. 2011. Pile Setup, Dynamic Construction Control, and Load and Resistance Factor Design of Vertically-Loaded Steel H-Piles. Ph.D. Thesis. Iowa State University. Ames, Iowa.



Pore water and lateral earth pressure measurement