PERFORMANCE EVALUATION OF A LARGE SCALE PILE LOAD TESTING PROGRAM IN LIGHT OF NEWLY DEVELOPED LRFD PARAMETERS

Reference

PERFORMANCE EVALUATION OF A LARGE SCALE PILE LOAD TESTING PROGRAM IN LIGHT OF NEWLY DEVELOPED LRFD PARAMETERS

Eric Thibodeau, P.E.¹, and Samuel G. Paikowsky, ScD²

ABSTRACT

A large load test program was performed by the Connecticut Department of Transportation (ConnDOT) as part of the Interstate I-95 New Haven Harbor Crossing Corridor Improvement Project. The extensive program included 23 statically load tested piles to failure in unique subsurface conditions containing glacio-deltaic deposits of silts and fine sands. The majority of the piles were dynamically monitored during driving and subsequent restrike tests.

This paper focuses on the evaluation of design methodologies, making use of the information related to the piles that were installed in two test areas (A and B). An extensive evaluation is carried out via the static and dynamic testing results. The outcomes are compared with existing pile databases, recommendations developed for the American Association of Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications for Deep Foundations (NCHRP 507, see Paikowsky, 2004), and current AASHTO Allowable Stress Design (ASD) Specifications (AASHTO, 2002). These comparisons enable assessment of the design and the construction prediction methods as well as the associated resistance factors. An attempt to compare ASD and LRFD parameters is made considering the load treatment of the different methodologies.

The accuracy of the static methods used during the design phase (in this specific site) was found to be marginally in agreement with the existing pile databases used for the LRFD parameter development (1 std dev removed). However, for the construction phase, the dynamic method capacity predictions compared well with the existing pile databases. Overall, the LRFD recommendations resulted with a more consistent design methodology when directly compared to the AASHTO ASD Specifications.

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PROJECT AND LOAD TEST PROGRAM OVERVIEW

In the spring and summer of 2002, the ConnDOT and their Program Manager Parsons Brinckerhoff Quade & Douglas (PBQ&D) performed an extensive pile load test program as part of the Interstate I-95 New Haven Harbor Crossing Corridor Improvement Project located in the cities of New Haven, East Haven, and Branford Connecticut; see Figure 1. The project includes the reconstruction of approximately 11.6 km of I-95, located between Exits 46 (New Haven) and 54 (Branford).

![Test Areas](image)

**Fig. 1. Locus Plan and Photograph Overview of Test Sites and Project Location**

**Sites and Contractors**

Four sites (designated test areas A through D) were selected for pile load testing. The program involved the installation of 43 piles, of which 23 were statically load tested to failure. The majority of the piles were dynamically monitored during driving and subsequent pile restrike tests. The primary purpose of the load test program was to evaluate the pile driving conditions and load carrying characteristics of several different pile types and lengths in order to develop final pile design and construction recommendations.

The load test program for areas A and B included the installation of 19 piles (designated A-1 through A-10 and B-1 through B-9) of varying types and dimensions. GZA GeoEnvironmental (GZA) of Norwood, Massachusetts provided field inspection services during pile driving operations, Pile Driving Analyzer™ (PDA)
monitoring, performance of static load tests, and signal matching analyses using the CAse Pile Wave Analysis Program (CAPWAP).

Pile Installation

Two hydraulic impact hammers were selected to drive the piles, a Hercules Machinery Corporation (HMC) Model 86 with a maximum energy rating of 86.8 kJ and an Hydraulic Power Systems, Inc. (HPSI) Model 2000 with a maximum energy rating of 108.5 kJ.

Two restrike tests were performed on each pile that was selected for static load testing. The first restrike test (BOR1) was performed between 1 and 3 days after driving and the second restrike test (BOR2) was performed between 8 and 23 days after driving. Dynamic measurements were obtained during the initial driving operation and during the first and second restrike tests. CAPWAP analyses were performed by GZA on one representative hammer blow from the end of initial driving and for each of the restrike tests.

Static Load Testing

Static load testing was performed on 11 out of the 19 piles installed in areas A and B. The static load tests (SLT) were performed after the second restrike test (BOR2), between 41 and 56 days after driving. The load tests were carried out to failure conditions using the Quick Load Test Method (ASTM D1143) (PBQ&D, 2002; GeoDesign, 2002; and GZA, 2002).

PILE LOAD TESTS AT AREAS A AND B

Subsurface Conditions

Four test borings were performed within the immediate vicinity of each of the testing sites. The general subsurface conditions consist of miscellaneous fill overlying organic estuarine and glacio-deltaic deposits. The fill ranged between 2 and 7 m in thickness and is most likely associated with the historic development of these sites and the construction of I-95. The organics ranged between 3 and 11 m in thickness and represents the original harbor bottom prior to development. The glacio-deltaic deposit was over 60 m in thickness and generally consists of a red brown, medium dense to very dense, mixture of fine to medium sand and silt, with interbedded layers of silt and clay (up to 6 m in thickness). Distinct gravel layers were also encountered within the deposit and ranged between 2 to 3 m in thickness.

Site Variability

The concept of site variability relates to the variation within similar subsurface strata located at a specific site and may be assessed by statistically analyzing in-situ test data such as SPT N-values. For areas A and B, the site variability was assessed in
accordance with NCHRP 507 (Paikowsky, 2004) whereby the SPT N-values were corrected, tabulated for each stratum, and the mean (m<sub>x</sub>), standard deviation (σ<sub>x</sub>), and coefficient of variation (COV) calculated for each layer assuming a normal distribution. Some SPT N-values were omitted from the dataset due to the presence of strata breaks within the sample interval, the presence of obstructions (i.e., cobbles, boulders, construction debris), and sample refusals with partial sampler penetration. The variability of each stratum was then classified using the COV ranges presented in NCHRP 507 and will be later used to calculate the factored resistance (R<sub>r</sub>) associated with the static load tests. The variability assessment is presented and summarized in Figure 2.

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>n</th>
<th>m&lt;sub&gt;x&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;x&lt;/sub&gt;</th>
<th>COV</th>
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</tr>
<tr>
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<td>16</td>
<td>19</td>
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n – Number of Values

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n – Number of Values

**Fig. 2. Site Variability Assessment for Areas A and B**

**Static Pile Capacity Predictions**

The nominal resistance (R<sub>n</sub>) for the 11 piles that were statically load tested was determined using the analysis methods/combinations presented in Table 1. Based upon the results of a questionnaire distributed to U.S. transportation agencies, these methods were recognized as the state of practice and selected for calibration of the
LRFD parameters presented in NCHRP 507 (Paikowsky, 2004). Three different combinations of analysis/design methods were produced for the pipe piles (PP) and square precast prestressed concrete piles (PPC). Since monotube piles (MT) were not included in the NCHRP 507 research, two analysis combinations were selected with a preference given to the Nordlund method (Nordlund, 1963) of analysis, which

Table 1. Predicted Static Nominal Resistance Summary

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Pile Type</th>
<th>DL (m)</th>
<th>Combination/Design Method</th>
<th>$R_n$ (kN)</th>
<th>SLT (kN)</th>
<th>SLT Date</th>
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</thead>
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<td>PPC (356mm)</td>
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<td>β-method/Thurman</td>
<td>3705</td>
<td>2180</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
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<td>34.9</td>
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<tr>
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<td>β-method/Thurman</td>
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<td>3025</td>
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<td>B-1</td>
<td>PP (457mm)</td>
<td>43.1</td>
<td>β-method/Thurman</td>
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<tr>
<td>B-3</td>
<td>PPC (406mm)</td>
<td>30.6</td>
<td>β-method/Thurman</td>
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<td>β-method/Thurman</td>
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<td>2002</td>
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<td>β-method/Thurman</td>
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<tr>
<td>B-9</td>
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<td></td>
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</table>

DL – Driven Pile Length
$R_n$ – Predicted Static Nominal Resistance
SLT – Static Load Test Nominal Resistance (Davisson’s failure criterion)
enabled consideration of the tapered pile sections. The soil parameter interpretations that were used to develop NCHRP 507 and the current evaluation were based on average SPT N-values and the soil property correlations presented by Kulhawy and Mayne (1990). Pile types, sizes, driven lengths, static load test interpreted failure loads, and the resulting estimated Rₙ’s are summarized in Table 1. The interpreted failure loads were evaluated using Davisson’s failure criterion (Davisson, 1972).

**Dynamic Testing and Dynamic Equation Predictions**

Signal matching analyses (CAPWAP) were performed for one representative blow for the end of driving (EOD), BOR1 and BOR2 conditions to evaluate the pile’s nominal resistance (Rₙ). The top of Pile A-1 broke after the second hammer blow during the BOR2; therefore, a CAPWAP analysis was not performed. The Energy Approach method (Paikowsky et al.1994) was also used to evaluate the pile’s capacity at EOD. The Energy Approach uses basic energy relations in conjunction with dynamic (PDA) measurements (E_max and D_max) and the permanent displacement (set) of the pile (1/measured blow count) to predict pile capacity. Results from the transportation agency questionnaire indicated that dynamic equations are still widely used in practice and are part of almost all specifications of the Department of Transportation across the USA. Three dynamic equations were selected and included in the NCHRP 507 (Paikowsky, 2004) recommendations as indicated in Table 2.

**PERFORMANCE EVALUATION**

**Comparison to NCHRP 507 Pile Databases**

The nominal resistance (Rₙ) predictions obtained from the static analyses, dynamic equations, and dynamic analyses were directly compared to the results obtained from the two pile databases that were used to develop the LRFD recommendations presented in NCHRP 507 (Paikowsky, 2004). In order to perform the comparison, the mean bias (λ) and standard deviation were calculated for each of the predictive methods as summarized in Table 3. The bias is defined as the ratio of the measured Rₙ (as obtained from the SLT) divided by the predicted Rₙ and is a direct measure of the relative accuracy of the prediction where a bias greater than 1.0 signifies an underprediction and a bias of less than 1.0 signifies an overprediction.

Overall, the mean bias for all of the static analysis combinations for areas A and B are lower than the mean bias obtained from the NCHRP 507 pile databases but are within one standard deviation. Statistics for the MT piles were not included in this comparison due to a limited dataset containing only 2 cases.

A similar approach was utilized to compare the results of the dynamic predictive methods. In order to make this comparison, the area ratio (AR) and the EOD blow count for each pile required further evaluation. Statistical research performed on the
Table 2. Summary of Pile Capacity Predictions Based on Dynamic Methods

<table>
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<tr>
<th>Pile No.</th>
<th>Time</th>
<th>Test Date</th>
<th>BC</th>
<th>E&lt;sub&gt;max&lt;/sub&gt; (kJ)</th>
<th>D&lt;sub&gt;max&lt;/sub&gt; (mm)</th>
<th>CAPWAP (kN)</th>
<th>EA (kN)</th>
<th>ENR (kN)</th>
<th>Gates (kN)</th>
<th>MG (kN)</th>
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<tr>
<td>A-1</td>
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<td>2131</td>
<td>3754</td>
<td>1623</td>
<td>1492</td>
<td>2859</td>
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<td>35.4</td>
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</table>

BC – Blow Count/Blows per 10 cm
E<sub>max</sub> – Max. Energy (PDA for CAPWAP Blow)
D<sub>max</sub> – Max. Pile Top Displacement (PDA)
EA – Energy Approach (Paikowsky et al.1994)
R<sub>n</sub> – Predicted Nominal Resistance

ENR – Engineering News Record
MG – FHWA Modified Gates Equation

(1) – BC Based on 21 Blows for 12.7mm
(2) – BC Based on 23 Blows for 12.7mm
(3) – BC Based on 40 Blows for No Penetration

piles contained in the NCHRP 507 databases identified the effects of soil acceleration and soil displacement as controlling parameters when utilizing EOD dynamic measurements to predict R<sub>n</sub> (Paikowsky et al. 1994, Paikowsky and Chernauskas, 1996). In particular, it has been shown that the energy loss through the work
performed by the displaced soil mass at the pile tip is directly related to the
acceleration of this mass (Holscher, 1995; Holscher and Barends, 1996; and Hajduk
et al. 2000). The influence of these accelerations may indirectly be evaluated through
the driving resistance, which represents the pile’s final displacement under each
hammer blow. For the case of low driving resistance (easy driving), high acceleration
and velocity are developed at the pile’s tip. For high driving resistance (hard driving),
there is small acceleration at the pile tip, which results in little (if any) mobilization of
the soil mass beyond the radiating elastic wave. Therefore, the corresponding energy
loss due to soil motion is small as compared to the easy driving condition. Based on
the NCHRP 507 research, the boundary between these effects was statistically
determined and defined as 16 blows per 10 cm.

Table 3. Summary of Comparisons Between the Analyzed Pile Load Tests and
NCHRP 507 Pile Databases

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Analysis Method/Time</th>
<th>Pile Load Test Areas A and B</th>
<th>NCHRP 507</th>
</tr>
</thead>
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<td></td>
<td>n</td>
<td>λ</td>
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<td>0.74</td>
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Static Methods

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<th>NCHRP 507</th>
</tr>
</thead>
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<td>Analysis Method/Time</td>
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<td>All ENR Equation – General</td>
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<tr>
<td>All Gates Equation – General</td>
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<tr>
<td>All FHWA Modified Gates – EOD</td>
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<tr>
<td>All FHWA Modified Gates - EOD(1)</td>
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<tr>
<td>All CAPWAP – EOD (2)</td>
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<td>All Energy Approach – EOD</td>
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Dynamic Methods

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<td>(1) – BC &lt; 16 BP10cm</td>
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<tr>
<td>(2) – BC &lt; 16 BP10cm &amp; AR &lt; 350</td>
</tr>
</tbody>
</table>

Piles are typically classified as being small displacement or large displacement piles.
As most soil displacement occurs at the pile tip, this classification can be better
served by calculating the pile’s area ratio (AR), which is defined as the ratio of the
pile’s embedded surface area divided by the pile tip area (Paikowsky et al., 1994). To
take this effect into consideration, a quantitative boundary between “small” and
“large” displacement piles of AR < 350 was proposed and, when considered in
conjunction with the effects of driving resistance, was confirmed with the statistical
research results obtained from the NCHRP 507 pile databases.
For dynamic predictions, NCHRP 507 recommended separate categories for blow count (BC) < 16 blows per 10 cm (i.e., easy driving) for the FHWA Modified Gates equation and (BC) < 16 blows per 10 cm and AR < 350 for CAPWAP analyses for the EOD condition. Of the eleven evaluated piles, ten satisfy the easy driving criterion and six satisfy both the easy driving and large displacement (AR < 350) criteria. As indicated in Table 3, the mean bias for all of the dynamic prediction methods compare well with the mean bias obtained from the NCHRP 507 pile databases except for the Modified Gates equation and the CAPWAP EOD for the six piles that satisfy the BC and AR special criteria. Overall, the Energy Approach method EOD and CAPWAP BOR2 yielded the most accurate $R_n$ predictions.

**LRFD Design Phase Evaluation – Static Analyses**

The LRFD resistance factors that were developed as part of NCHRP 507 (Paikowsky, 2004) were examined via a comparison with the commonly used AASHTO Allowable Stress Design (ASD) Specifications (AASHTO, 2002). The predicted nominal resistances ($R_n$) obtained from the static analyses were multiplied by the NCHRP 507 recommended resistance factors in order to obtain the factored resistance ($R_r$) as summarized in Table 4.

The NCHRP 507 resistance factors presented in Table 4 were developed using statistical parameters with consideration given to subsurface soil profile type (e.g., sand, clay, or mixed), pile type (e.g., PPC, PP, or H-pile), analysis method/combination, and a target reliability level considering whether or not the piles are constructed as part of a redundant or non-redundant foundation system (assumed to be redundant for this evaluation). Since NCHRP 507 research did not include the MT pile type, the resistance factors recommended for PP piles were alternatively used to evaluate $R_r$ for the MT piles.

An approximate equivalent LRFD factor of safety (LRFD FS) was evaluated using the following relationships, which consider the LRFD dead load and live load factors associated with the LRFD Strength I Load Combination (AASHTO, 1998):

$$\gamma_w = \gamma_{DL} \left( \frac{DL}{LL} \right) + \gamma_{LL} \left( \frac{DL}{LL} \right) + 1$$

and

$$LRFD\ FS = FS*\gamma_w$$

Where:

$\gamma_w$ = weighted load factor
$\gamma_{DL} =$ Load Factor for Dead Load = 1.25
$\gamma_{LL} =$ Load Factor for Live Load = 1.75
$DL/LL =$ Dead Load/Live Load Ratio (assumed 3)
LRFD FS = Approximate LRFD Factor of Safety
$FS =$ SLT $R_n/R_r$
### Table 4. Design Phase Evaluation—Static Analyses

<table>
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<tr>
<th>Pile Type</th>
<th>Pile No.</th>
<th>Prediction Method</th>
<th>$R_n$ (kN)</th>
<th>$\phi$</th>
<th>$R_r$ (kN)</th>
<th>SLT (kN)</th>
<th>FS</th>
<th>LRFD FS</th>
<th>ASD FS</th>
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<td>1661</td>
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<td>1.66</td>
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</tbody>
</table>

- $R_n$ – Predicted Nominal Resistance
- $\phi$ – Resistance Factor (Paikowsky, 2004)
- $R_r$ – Factored Resistance ($\phi R_n$)
- SLT – Measured Nominal Resistance ($R_n$)
- FS – Factor of Safety = SLT $R_r$/$R_n$
- $\gamma_u$ – Load Factor = 1.375 (DL/LL = 3)
- LRFD FS – $FS*\gamma_u$ (approx. ASD FS)
- ASD FS = SLT/$R_n$/3.5

As shown in Table 4, the equivalent LRFD FS values ranged between 1.07 (pile B-5) and 3.36 (pile A-8). The factor of safety as determined from the current ASD Specifications was also calculated. The ASD factor of safety (ASD FS) was calculated by dividing the predicted $R_n$ (ASD equivalent ultimate capacity) by 3.5 to obtain the ASD equivalent allowable capacity. The measured ultimate capacity, as
obtained from the SLT, was then divided by the allowable capacity to obtain the actual ASD FS. Actual ASD FS values varied between 0.95 (pile B-5) and 2.83 (pile B-3).

**LRFD Construction Phase Evaluation – Static Load Tests**

Based on NCHRP 507 (Paikowsky, 2004), resistance factors to be applied to the interpreted failure load were developed with consideration given to the number of load tests performed at a given site, the site variability, and the variability introduced by the selected static load test failure criterion (i.e., Davisson’s failure criterion). These three factors were selected since observed pile capacity differences for a certain type of static load test that is performed at the same site on the same pile type would only be reflective of spatial soil variability across the site, the inherent variability of the method used to evaluate the interpreted failure load, and the reduction of the uncertainty in the test results when increasing the number of tests performed. As discussed previously, the site variability is based upon statistical assessment of in-situ test data. The recommended resistance factors for static load tests with respect to site variability (COV ranges) and the number of load tests to be performed for a given site are summarized in Table 5.

**Table 5. Recommended Resistance Factors for SLT (Paikowsky, 2004)**

<table>
<thead>
<tr>
<th>No. of Load Tests Per Site</th>
<th>Recommended Resistance Factor ($\phi$)</th>
<th>Site Variability</th>
</tr>
</thead>
<tbody>
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<td>Low (COV &lt; 25%)</td>
<td>Medium (25% (\leq) COV &lt; 40%)</td>
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<tr>
<td>1</td>
<td>0.80</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>0.90</td>
<td>0.75</td>
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<tr>
<td>3</td>
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</tr>
<tr>
<td>$\geq$ 4</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The variability of the principal bearing layer (see Figure 2) was considered when selecting the appropriate resistance factor. The resulting factored resistances ($R_r$) and equivalent LRFD FS values (assuming the performance of two load tests) are summarized in Table 6.

The equivalent LRFD FS values varied between 1.83 and 2.12 for resistance factors of 0.75 and 0.65, respectively. These values are generally consistent with current ASD Specifications for this level of construction quality control, though somewhat lower (1.83 compared to 2.0) for strata identified as medium variability with two load tests.

**LRFD Construction Phase Evaluation – Dynamic Equations**

The resistance factors associated with the dynamic equations along with their corresponding factored resistances ($R_r$) are presented and summarized in Table 7.
Equivalent LRFD FS values for the ENR equation ranged between 5.73 and 13.38 and are considered to be too conservative for current design practice but correctly represent the low accuracy and high variability of the method. LRFD FS values for the Gates equation ranged between 2.60 and 4.80. For six of the eleven cases, the equivalent LRFD FS values were slightly higher for the FHWA Modified Gates equation, ranging between 2.62 and 4.74. ASD FS values were calculated by applying a factor of safety of 3.5 to the dynamic equation nominal resistance ($R_n$). As compared to the equivalent LRFD FS values, the ASD FS values yielded consistently lower factors of safety for the ENR and FHWA Modified Gates equations but higher factors of safety for the Gates equation.

### Table 6. Construction Phase Evaluation - Static Load Tests

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Principal Bearing Stratum</th>
<th>Site Variability</th>
<th>SLT (kN)</th>
<th>$\phi$</th>
<th>$R_r$ (kN)</th>
<th>FS</th>
<th>LRFD FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>Glacio-Deltaic - Upper</td>
<td>Medium</td>
<td>2180</td>
<td>0.75</td>
<td>1635</td>
<td>1.33</td>
<td>1.83</td>
</tr>
<tr>
<td>A-2</td>
<td>Glacio-Deltaic - Upper</td>
<td>Medium</td>
<td>2669</td>
<td>0.75</td>
<td>2002</td>
<td>1.33</td>
<td>1.83</td>
</tr>
<tr>
<td>A-6</td>
<td>Glacio-Deltaic - Upper</td>
<td>Medium</td>
<td>3025</td>
<td>0.75</td>
<td>2269</td>
<td>1.33</td>
<td>1.83</td>
</tr>
<tr>
<td>A-7</td>
<td>Glacio-Deltaic - Upper</td>
<td>Medium</td>
<td>2771</td>
<td>0.75</td>
<td>2078</td>
<td>1.33</td>
<td>1.83</td>
</tr>
<tr>
<td>A-8</td>
<td>Glacio-Deltaic - Upper</td>
<td>Medium</td>
<td>1592</td>
<td>0.65</td>
<td>1194</td>
<td>1.54</td>
<td>2.12</td>
</tr>
<tr>
<td>B-1</td>
<td>Glacio-Deltaic - Middle</td>
<td>Medium</td>
<td>2269</td>
<td>0.65</td>
<td>1701</td>
<td>1.54</td>
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</tr>
<tr>
<td>B-3</td>
<td>Glacio-Deltaic - Upper</td>
<td>High</td>
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<td>1850</td>
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<td>B-5</td>
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<td>Medium</td>
<td>3683</td>
<td>0.75</td>
<td>2762</td>
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<tr>
<td>B-6</td>
<td>Glacio-Deltaic - Upper</td>
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<td>B-9</td>
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<td>0.65</td>
<td>1272</td>
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<td>2.12</td>
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SLT – Measured Nominal Resistance ($R_n$)  
$\phi$ – Resistance Factor (Table 5)  
$R_r$ – Factored Resistance ($\phi*R_n$)  
FS – Factor of Safety = SLT/$R_r$  
$\gamma_w$ – Load Factor = 1.375 (DL/LL = 3)  
LRFD FS – FS*$\gamma_w$ (approx. ASD FS)

### LRFD Construction Phase Evaluation – Dynamic Analyses

The resistance factors associated with the dynamic capacity analyses along with their corresponding factored resistances ($R_r$) are presented and summarized in Table 8. The NCHRP 507 (Paikowsky, 2004) resistance factors presented in Table 8 were developed using statistical parameters with consideration given to the time that the dynamic measurements were taken (i.e., EOD, BOR1, BOR2), the effects of soil motion, the effects of the volume of the displaced soil, and whether the pile would be part of a redundant or non-redundant foundation system (assumed to be redundant for this evaluation). As discussed previously, the boundary between soil motion effects was statistically determined and defined as 16 blows per 10 cm and the quantitative boundary between “small” and “large” displacement piles was determined to be piles with an AR < 350. This special condition applies to six of the eleven piles and only for the CAPWAP analyses that were performed for the EOD condition.

Equivalent LRFD FS values associated with the CAPWAP analyses decreased with increasing test times and is due to the more reliable capacity predictions provided by
the BOR1 and BOR2 and may be attributed to pile “setup”. Although the Energy Approach is not currently listed as an ASD construction quality control method, it yields equivalent LRFD FS values that are generally consistent with those used for analyses utilizing dynamic measurements for quality control.

Table 7. Construction Phase Evaluation - Dynamic Equations

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Prediction Method</th>
<th>$R_n$ (kN)</th>
<th>$\phi$</th>
<th>$R_r$ (kN)</th>
<th>SLT (kN)</th>
<th>FS</th>
<th>LRFD FS</th>
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<td>0.25</td>
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<td>1119</td>
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</table>

$R_n$ – Predicted Nominal Resistance  
$\phi$ – Resistance Factor (Paikowsky, 2004)  
$R_r$ – Factored Resistance ($\phi*R_n$)  
$\gamma_w$ – Load Factor = 1.375 (DL/LL = 3)  
$\text{LRFD FS} = \text{FS}^*\gamma_w$ (approx. ASD FS)  
$\text{ASD FS} = \text{SLT}/(R_r/3.5)$  
$R_n$ – Predicted Nominal Resistance  
$\phi$ – Resistance Factor (Paikowsky, 2004)  
$R_r$ – Factored Resistance ($\phi*R_n$)  
$\gamma_w$ – Load Factor = 1.375 (DL/LL = 3)  
$\text{LRFD FS} = \text{FS}^*\gamma_w$ (approx. ASD FS)  
$\text{ASD FS} = \text{SLT}/(R_r/3.5)$
Table 8. Construction Phase Evaluation - Dynamic Analyses

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Prediction Method</th>
<th>$R_n$ (kN)</th>
<th>$\phi$</th>
<th>$R_r$ (kN)</th>
<th>SLT (kN)</th>
<th>FS</th>
<th>LRFD FS</th>
<th>ASD FS</th>
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$R_n$ – Predicted Nominal Resistance
$\phi$ – Resistance Factor (Paikowsky, 2004)
$R_r$ – Factored Resistance ($\phi R_n$)
SLT – Measured Nominal Resistance ($R_n$)
FS – Factor of Safety = SLT $R_n$/R_r
$\gamma_w$ – Load Factor = 1.375 (DL/LL = 3)
LRFD FS – FS* $\gamma_w$ (approx. ASD FS)
ASD FS = SLT/($R_n$/2.25)

(1) – BC < 16 BP10cm & AR < 350
ASD FS values were calculated by applying a factor of safety of 2.25 to the dynamic analysis nominal resistance \( (R_o) \). Factors of safety associated with the Energy Approach were evaluated assuming an ASD FS of 2.25 though this method is not specifically addressed in the AASHTO ASD Specification. As compared to the equivalent LRFD FS values, the ASD Specifications yielded lower factors of safety for six of the eleven piles associated with the CAPWAP and Energy Approach for the EOD condition but higher factors of safety for the CAPWAP BOR1 and BOR2 were realized for all other pile cases.

**Comparison of the Actual Safety Margin of the Recommended LRFD Parameters to the Current AASHTO ASD Specifications**

The equivalent LRFD FS values obtained from the static analyses, dynamic equations, and dynamic analyses are summarized and statistically compared to the ASD FS values in Table 9.

<table>
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<tr>
<th>Pile Type</th>
<th>Analysis Method/Time</th>
<th>LRFD FS ( n )</th>
<th>LRFD FS ( m_x )</th>
<th>LRFD FS ( \sigma_x )</th>
<th>ASD FS ( n )</th>
<th>ASD FS ( m_x )</th>
<th>ASD FS ( \sigma_x )</th>
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\( n \) – number of cases  
\( m_x \) – Mean LRFD FS or ASD FS  
\( \sigma_x \) – standard deviation  
\( \text{(1)} \) – ASD FS of 2.25 used for EA EOD

Overall, the NCHRP 507 (Paikowsky, 2004) recommendations and ASD Specifications yielded similar results (e.g., mean FS and standard deviation) for the three static prediction methods/combinations associated with the PPC piles. However, the NCHRP 507 recommendations yielded higher and more reasonable factors of safety for the PP piles, which are more in line with the state of practice. ASD factors of safety varying around 1.5 (0.95 to 2.14, see Table 4) are below what can be
considered as a safe margin. Statistics for the MT piles were not included in this comparison due to a limited dataset of only 2 cases.

Regarding the dynamic equations, the ASD Specifications yielded lower (less conservative) factors of safety and standard deviations for the ENR and FHWA Modified Gates equations while the NCHRP 507 recommendations yielded lower (less conservative) factors of safety for the Gates equation. Regarding the dynamic analyses, the ASD Specifications yielded slightly lower factors of safety and standard deviations for the CAPWAP and Energy Approach analyses for the EOD condition while the NCHRP 507 recommendations yielded slightly lower factors of safety and standard deviations for the CAPWAP BOR1 and BOR2 analyses.

CONCLUSIONS

Based on the presented data and information, the following conclusions may be derived:

1. The use of extensive pile databases for performing statistical based calibration of LRFD parameters was proven to be effective even for the investigated site where the difficult subsurface conditions resulted in very high (non-conservative) static capacity predictions.

2. Using the NCHRP 507 LRFD recommended resistance factors for the static analyses generally yielded higher LRFD equivalent factors of safety for all piles (especially the pipe piles) and all analyses (31 cases) as compared with the ASD FS values (see Tables 4 and 9). The NCHRP 507 recommended resistance factors resulted in more reasonable design values that accounted for the bias of the method in comparison with the single factor of safety of 3.5 used by the ASD Specifications that ultimately resulted with a non-conservative design for the monotube and pipe piles and specifically for pile B-5 (FS<1).

3. Despite the fact that the NCHRP 507 recommended resistance factors for the static analyses performed better than the ASD Specifications (see above), the mean predictions for all of the piles at the analyzed sites were significantly lower than those used for the development of the NCHRP 507 recommendations (see Table 3). The greater overpredictions are due to the overestimation of soil properties associated with the glacio-deltaic deposits which suggests that local calibration of LRFD parameters (i.e., resistance factors) should be considered to accommodate geographically soil specific conditions.

4. The LRFD equivalent factors of safety values associated with the static load test results ranged between 1.83 and 2.12. These values are generally consistent with the recommended ASD factor of safety of 1.9 to 2.0. However, for projects that contain sites that exhibit lower site variability and/or sites where more load tests are performed, a higher resistance factor may be used which will result in lower LRFD equivalent factors of safety. Such considerations result with a higher construction phase factored resistances (R_5) and therefore a more economical design overall. As such the performance of static load tests (even when using LRFD) continues to play an important role and should, when deemed necessary,
be used in conjunction with dynamic measurements for construction quality control.

5. Of the evaluated dynamic analyses, the Energy Approach was found to be the most effective for the EOD condition and the CAPWAP BOR1/BOR2 was shown to be accurate for pile restrike tests. Both analyses are important. EOD dynamic measurements are significant for determining hammer performance and establishing driving criteria and hence the Energy Approach method has an important benefit in that it uses EOD dynamic PDA measurements to predict long-term pile capacity. For this reason, the Energy Approach may be utilized in the field as a cost effective construction quality control measure to accurately assess a pile’s nominal resistance ($R_n$) when implementing LRFD or ultimate capacity when implementing ASD. The method has the potential to eliminate the need for waiting periods, equipment requirements, and office analysis cost and delays associated with restrike tests. The signal matching analyses at restrike (CAPWAP BOR1/BOR2) were shown to be extremely effective to predict the $R_n$ during restrike and hence to follow situations where pile capacity changes with time. The combination, therefore, of measurements and analyses (Energy Approach EOD and CAPWAP BOR) seem to provide the best of both conditions and independently affirms the dynamic measurements, especially for sites where capacities may significantly increase or, more importantly, decrease with time.

6. The evaluated dynamic equations resulted with excessive factors of safety when used with either the NCHRP 507 recommended resistance factors or the ASD Specifications. However, it is shown that the NCHRP 507 bias correction resulted in more reasonable and consistent LRFD equivalent factors of safety for the Gates and the FHWA Modified Gates equations. If dynamic equations are to be utilized as a construction quality control method then the Gates or the FHWA Modified Gates with the NCHRP 507 resistance factors are recommended (see Tables 7 and 9).

7. The dynamic equations for the monotube piles were found to be extremely underpredictive for both the NCHRP 507 resistance factors and the ASD Specifications (especially the ENR equation). This observation is also correct for the dynamic measurements at the EOD using the CAPWAP analyses. Of the seven construction quality control methods evaluated, the CAPWAP BOR2 analysis and Energy Approach for the EOD condition performed the best for the monotube piles. Also, one of the selected static analysis prediction combinations ($\alpha$-Tomlinson/Nordlund/Thurman) along with the recommended resistance factor for pipe piles, seemed to yield acceptable LRFD equivalent factors of safety. These conclusions are restricted by the two evaluated cases and therefore cannot be considered conclusive.

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REFERENCES


