Lecture 6 - Standards and Reliability Based Design

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1 DESIGN PRACTICE
Every state in the USA has a building code which is part of the state’s laws. In addition, the Department of Transportation (a.k.a. Highway Department) of the state has its specifications.

The construction of most bridges (all highway bridges) is funded mostly by the Federal Government via FHWA. All these structures are obliged to be designed by the AASHTO specifications.

A united code (IBC – International Building Code) was developed in 2000 by uniting several previous codes (UBC – Uniform Building Code and SBC – Standard Building Code). Forty-four states (88%) adopted the IBC as their building code.
1 DESIGN PRACTICE
Codes in the USA

- The standard (old) AASHTO specifications recommended a F.S. = 3.00 for B.C. of shallow foundations. The AASHTO specifications do not provide FS for settlement though requires to examine settlement.

- The AASHTO Specifications, as well as most advanced codes worldwide, moved to RBD – Reliability Based Design. The LRFD – Load and Resistance Factor Design format of RBD is used by the AASHTO specifications, and the major developments relevant to pile design in general and dynamic testing in particular will be presented.
1 DESIGN PRACTICE

Limit State Requirements

A design of a structure needs to ensure that while being economically viable it will suit the intended purpose during its working life.

LS – Limit State – Condition beyond which the structure or a component fail to fulfill in some way the intended purpose for which it was designed.

ULS – Ultimate Limit State – deals with strength (maximum loading capacity) of the structure / element. (aka Strength Limit State)

SLS – Serviceability Limit State – deals with the functionality and service requirements of a structure to ensure adequate performance under expected conditions.

Relevance to Shallow Foundations:
By and large design of shallow foundations on soils is controlled by SLS and design of shallow foundations on rock by SLS. IGM’s can go either way depending on density and cementation.
## 1 DESIGN PRACTICE

### Shallow Foundations Design Process

shown in Table C-6 and in the LRFD design process flow chart, Figure C-1.

**TABLE C-6: STEPS IN LRFD DESIGN PROCESS FOR BRIDGE SUPPORTED ON SHALLOW FOUNDATIONS**


<table>
<thead>
<tr>
<th>Step</th>
<th>LRFD Design Activity</th>
<th>Responsible Disciplines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Develop <strong>preliminary bridge layout</strong>. The desired bridge type, size and location will be established. Span lengths and pier locations will be defined, considering geometrical and environmental constraints.</td>
<td>Structural, in coordination with general civil and environmental considerations and geotechnical for approach stability</td>
</tr>
<tr>
<td>2.</td>
<td>Determine the shallow foundation feasibility based on <strong>review of existing geologic and subsurface data</strong>. Competent bearing material must be present within a reasonable distance from the ground surface. A preliminary assessment of approach embankment stability should be conducted to evaluate potential impacts to abutment locations and span lengths. (Section 4.1).</td>
<td>Geotechnical, in coordination with structural, general and environmental</td>
</tr>
<tr>
<td>3.</td>
<td>A <strong>site reconnaissance</strong> with the structural and general civil engineer should be completed at this stage to evaluate constructability of foundation types (Section 4.2).</td>
<td>Geotechnical, in coordination with structural, general and environmental</td>
</tr>
<tr>
<td>4.</td>
<td>Determine the <strong>depth of the footing</strong> so that it will not be susceptible to <strong>scour potential</strong> or <strong>frost</strong> (Section 6.2).</td>
<td>Hydraulic, with geologic input from geotechnical</td>
</tr>
<tr>
<td>5.</td>
<td>Determine the <strong>loads</strong> applied to the footing (Section 6.3).</td>
<td>Structural</td>
</tr>
<tr>
<td>6.</td>
<td>Determine the design soil properties from the <strong>subsurface exploration</strong> and laboratory <strong>testing</strong> program (Sections 4.3 and 4.4).</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>7.</td>
<td>Calculate the <strong>nominal bearing resistance</strong>, based on effective footing width, B_e (Section 5.2) at the <strong>strength and extreme</strong> limit states.</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>8.</td>
<td>Calculate the <strong>nominal bearing resistance</strong> based on effective footing dimensions at the <strong>service limit state</strong> (Section 5.3).</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>9.</td>
<td>Calculate the <strong>sliding</strong> and <strong>passive soil resistance</strong> at the <strong>strength and extreme</strong> limit state (Section 5.4).</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>10.</td>
<td>When overall stability of the footing may govern the design (e.g., footings on or near slopes), perform a <strong>global stability analysis</strong> of the footing using service (unfactored) loads (Section 5.4).</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>11.</td>
<td>Size the <strong>footing dimensions</strong> at the service limit state (Section 6.4.1).</td>
<td>Structural</td>
</tr>
<tr>
<td>12.</td>
<td>Check the <strong>bearing pressure</strong>, <strong>maximum eccentricity</strong> and <strong>sliding</strong> at the <strong>strength limit state</strong> (Sections 6.4.3 and 6.4.4).</td>
<td>Structural</td>
</tr>
<tr>
<td>13.</td>
<td>Check the <strong>bearing pressure</strong>, <strong>maximum eccentricity</strong> and <strong>sliding</strong> at the <strong>extreme limit state</strong> (Sections 6.4.3 and 6.4.4).</td>
<td>Structural</td>
</tr>
<tr>
<td>14.</td>
<td>Complete the <strong>structural design</strong> of the footing using factored loads according to the concrete section of the specification (AASHTO, 1998).</td>
<td>Structural</td>
</tr>
</tbody>
</table>
1 DESIGN PRACTICE

Shallow Foundations
Design Process

Figure C-1: LRFD Design Process Flow Chart – Bridge Shallow Foundations

2 DESIGN METHODOLOGIES
STATE OF STRESS DESIGN

Working stress design (WSD) also called the Allowable Stress Design (ASD) method, has been used in Civil Engineering since the early 1800s.

\[ Q \leq Q_{all} = \frac{R_n}{F_S} = \frac{Q_{ult}}{F_S} \]

- \( Q = \) Design load (F)
- \( Q_{all} = \) Allowable load (F)
- \( R_n = Q_{ult} = \) Nominal Resistance = Ultimate geotechnical pile force resistance
- \( F_S = \) Factor of safety

The factor of safety is commonly defined as the ratio of the resistance of the structure (\( R_n \)) to the load effects (\( Q \)) acting on the structure.
2 DESIGN METHODOLOGIES
Review - Working Stress Design

ADVANTAGES

- Simple
- Vast Experience – Serves as a Reference

LIMITATIONS

- Lumps all uncertainty into a factor of safety
- Does not provide a direct evaluation of whether a method is conservative or un-conservative
## 2 DESIGN METHODOLOGIES

### Review - Working Stress Design


<table>
<thead>
<tr>
<th>X - Construction Control Specified on Plans</th>
<th>Increasing Construction Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsurface Exploration</td>
<td>X</td>
</tr>
<tr>
<td>Static Calculation</td>
<td>X</td>
</tr>
<tr>
<td>Dynamic Formula</td>
<td>X</td>
</tr>
<tr>
<td>Wave Equation</td>
<td>X</td>
</tr>
<tr>
<td>CAPWAP Analysis</td>
<td></td>
</tr>
<tr>
<td>Static Load Test</td>
<td></td>
</tr>
<tr>
<td><strong>Factor of Safety (FS)</strong></td>
<td><strong>3.50</strong></td>
</tr>
</tbody>
</table>

* Any combination that includes a static load test

Design Capacities Specified on Plans so FS can be Adjusted if Construction Control is Altered
1. On the face of it ⇒ logical and progressive but on what basis are the specifications founded? Is the control method F.S. suitable for the design method?

2. Rewards the use of quality control through dynamic measurements during driving and/or static load-testing.

3. Very Generic ⇒ Does not provide any details regarding the methods. e.g.:
   - What kind of subsurface investigation?
   - What kind of static analysis?
   - Dynamic Measurements - When? (EOD, Restrike ?) On what kind of piles? Driving conditions?
   - What about field interpretation?

   □□ Can be examined and/or explained only against actual data.
### SIMPLE EXAMPLE

Assume a load of 200 tons and Pile Capacity $Q_{ult} = 100$ tons (accurately predicted by all methods, i.e. bias = 1.0)

<table>
<thead>
<tr>
<th>Capacity Evaluation Method</th>
<th>F.S.</th>
<th>Load per Pile (tons)</th>
<th># of Piles</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Analysis</td>
<td>3.50</td>
<td>28.6</td>
<td>7.0</td>
<td>-</td>
</tr>
<tr>
<td>WEAP</td>
<td>2.75</td>
<td>36.4</td>
<td>5.5</td>
<td>-21%</td>
</tr>
<tr>
<td>CAPWAP</td>
<td>2.25</td>
<td>44.4</td>
<td>4.5</td>
<td>-36%</td>
</tr>
<tr>
<td>Static L.T.</td>
<td>2.00</td>
<td>50.0</td>
<td>4.0</td>
<td>-43%</td>
</tr>
</tbody>
</table>
Evaluation of Parameters - Driven Piles In Clay

No. of cases and Mean of Prediction
(msd. Over calculated using data ± 2 SD)

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Method</th>
<th>α API</th>
<th>α Tomlinson</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td>17</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Pipe</td>
<td></td>
<td>19</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>16</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>52</td>
<td>51</td>
<td>53</td>
</tr>
</tbody>
</table>

(1/0.8 = 1.25)

Actual Mean FS for driven piles in clay

<table>
<thead>
<tr>
<th>Method</th>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>0.82</td>
<td>2.87</td>
</tr>
<tr>
<td>λ</td>
<td>0.72</td>
<td>2.52</td>
</tr>
</tbody>
</table>

For Comparison – FS for the Dynamic Methods

CAPWAP - BOR 162 Mean = 1.16
Actual FS BOR = 1.16 x 2.25 = 2.61
Revisit Simple WSD Example

Assume a load of 200 tons and Pile Capacity $Q_{ult} = 100$ tons (Specifying now a concrete pile in clay and using the bias known for the methods)

<table>
<thead>
<tr>
<th>Capacity Evaluation Method</th>
<th>F.S. (Load)</th>
<th>Load per Pile - ton (w/o bias)</th>
<th># of Piles (w/o bias)</th>
<th>Savings (w/o bias)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Analysis $\alpha$ API Clay</td>
<td>3.50 on 123t</td>
<td>35.3 (28.6)</td>
<td>5.7 (7)</td>
<td>-</td>
</tr>
<tr>
<td>WEAP EOD</td>
<td>2.75 on 60t</td>
<td>22.0 (36.4)</td>
<td>9.1 (5.5)</td>
<td>+60% (-21%)</td>
</tr>
<tr>
<td>CAPWAP BOR</td>
<td>2.25 on 86t</td>
<td>38.4 (44.4)</td>
<td>5.2 (4.5)</td>
<td>-9% (-36%)</td>
</tr>
<tr>
<td>Static L.T.</td>
<td>2.00 on 100t</td>
<td>50.0</td>
<td>4.0</td>
<td>-30% (-43%)</td>
</tr>
</tbody>
</table>

(values in original example ignoring the bias)
INTERMEDIATED CONCLUSION

1. The examination of factors of safety on the basis of their absolute values is misleading and do not represent the economical value of a specific method.

2. The same holds for any other design method – e.g resistance factors for LRFD as will be shown.

3. Only the use of an actual database provides the bias of a design method and hence allows for a rational development of safety margins – regardless of the design methodology.
Uncertainties - Structural Design

Simplified Example of Beam Design and Sources of Uncertainty

Sources of Uncertainty

1. Loading
2. Dimensions
3. Material Properties

Most Noticeable:

1. No uncertainty in the model – under given loading conditions the uncertainty in the material properties (i.e. yield) dictates the uncertainty in strength or uncertainty in Modulus E will dictate the uncertainty in the deflection
2. Largest uncertainty in the loading, source, magnitude, distribution (in case of bridges)

(Assuming homogenous cross-section, horizontal symmetry line and beam height, h.)
Uncertainties - Geotechnical Design

Components of Foundations Design and Sources of Uncertainty

- Soil sampling and testing for engineering material parameters
- Uncertainty due to site, material and testing variability and estimation of parameters
- Code of practice
- Traditional design although developed over many years and used as a benchmark has undocumented unknown uncertainty

Uncertainty in loads created by and applied to the bridge, e.g.
- Dead Load – e.g. weight of the bridge
- Live Load – e.g. traffic and its effects (e.g. breaking)
- Wind & wind on traffic
- Extreme Events – e.g. earthquake, ship collision

Method of Approach

- LOAD Use the load uncertainty from the structures (until better research is done)
- RESISTANCE Establish the uncertainty of the “complete” foundation capacity analysis by comparing a design procedure to measured failure.

Assumed Failure Pattern under Foundations

Uncertainty in the assumptions made in the model development leaves unknown analysis versus actual performance

Analysis Model

LOAD Use the load uncertainty from the structures (until better research is done)
RESISTANCE Establish the uncertainty of the “complete” foundation capacity analysis by comparing a design procedure to measured failure.

Foundation Design

Loading

14.533 - Advanced Foundation Engineering
2 DESIGN METHODOLOGIES
Uncertainties - Geotechnical Design

Significant uncertainties exist in:

(1) The process of defining geomaterial properties.

(2) The calculation model.

- Defining uncertainty in the soil properties alone is therefore not sufficient in most cases to determine the uncertainty of the designed element/structure.

- The relationship between loads and displacements requires a separate model having its own uncertainty.
3 LOAD AND RESISTANCE FACTOR DESIGN (LRFD)
The design of a foundation depends upon predicted loads and the pile’s capacity to resist them. Both loads and resistance (capacity) have various sources and levels of uncertainty that historically have been compensated for by experience and subjective judgment. These uncertainties can be quantified using probability-based design, or safety check expressions, aimed at achieving designs with consistent levels of reliability. The intent of the Load and Resistance Factor Design (LRFD) method is to separate uncertainties in loading from uncertainties in resistance and to assure a prescribed margin of safety.
3 LRFD DESIGN
Probability Density Functions for Load and Resistance

An illustration of probability density functions for load effect and resistance

Q, R – Mean Load/Resistance
Q_n, R_n – Nominal Load/Resistance
consistent levels of reliability
The limit state function \( g \) corresponds to the margin of safety, i.e. the subtraction of the load from the resistance such that (referring to Figure 2a):

\[
g = R - Q
\]  

(4)

For areas in which \( g < 0 \), the designed element or structure is unsafe as the load exceeds the resistance. The probability of failure, therefore, is expressed as the probability for that condition:

\[
p_f = P(g < 0)
\]  

(5)

In calculating the prescribed probability of failure \( (p_f) \), a derived probability density function is calculated for the margin of safety \( g(R, Q) \) (refer to Figure 2a), and reliability is expressed using the “reliability index”, \( \beta \). Referring to Figure 2b, the reliability index is the number of standard deviations of the derived PDF of \( g \), separating the mean safety margin from the nominal failure value of \( g \) being zero:

\[
\beta = \frac{m_g}{\sigma_g} = \left( \frac{m_R - m_Q}{\sqrt{\sigma_Q^2 + \sigma_R^2}} \right)
\]  

(6)

where \( m_g, \sigma_g \) are the mean and standard deviation of the safety margin defined in the limit state function Eq. (4), respectively.
3 LRFD DESIGN
Probability of Failure and Target Reliability

Figure 2. An illustration of probability density function for (a) load, resistance and performance function, and (b) the performance function \( g(R,Q) \) demonstrating the margin of safety \( p_f \) and its relation to the reliability index \( \beta \). \( \sigma_g \) = standard deviation of \( g \).
Reliability is expressed using the “reliability index”, $\beta$, which is the number of standard deviations of the derived PDF of $g$, $g = R - Q$.

An Illustration of a Combined Probability Density Function ($g(R,Q)$) Representing the Margin of Safety and the Reliability Index, $\beta$ ($\sigma_g =$ Standard Deviation of $g$).

### Relationship Between Reliability Index and Target Reliability

<table>
<thead>
<tr>
<th>Reliability Index $\beta$</th>
<th>Probability of Failure $P_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.159</td>
</tr>
<tr>
<td>1.2</td>
<td>0.115</td>
</tr>
<tr>
<td>1.4</td>
<td>0.0808</td>
</tr>
<tr>
<td>1.6</td>
<td>0.0548</td>
</tr>
<tr>
<td>1.8</td>
<td>0.0359</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0228</td>
</tr>
<tr>
<td>2.2</td>
<td>0.0139</td>
</tr>
<tr>
<td>2.4</td>
<td>0.00820</td>
</tr>
<tr>
<td>2.6</td>
<td>0.00466</td>
</tr>
<tr>
<td>2.8</td>
<td>0.00256</td>
</tr>
<tr>
<td>3.0</td>
<td>0.00135</td>
</tr>
<tr>
<td>3.2</td>
<td>6.87 E-4</td>
</tr>
<tr>
<td>3.4</td>
<td>3.37 E-4</td>
</tr>
<tr>
<td>3.6</td>
<td>1.59 E-4</td>
</tr>
<tr>
<td>3.8</td>
<td>7.23 E-5</td>
</tr>
<tr>
<td>4.0</td>
<td>3.16 E-5</td>
</tr>
</tbody>
</table>
For the strength limit state:

\[ R_r = \phi R_n \geq \eta \sum \gamma_i Q_i \]

- \( R_r \) = Factored resistance (F or F/A);
- \( \phi \) = Resistance factor (dimensionless);
- \( R_n \) = Nominal (Ultimate) resistance (F or F/A);
- \( \eta \) = Factors to account for ductility (\( \eta_D \)), redundancy (\( \eta_R \)), and operational importance (\( \eta_I \)) – Structural (dimensionless)
- \( \gamma_i \) = Load factor (dimensionless);
- \( Q_i \) = Force effect, stress or stress resultant (F or F/A);
3 LRFD DESIGN
The Calibration Process

The problem facing the LRFD analysis in the calibration process is to determine the load factor (γ) and the resistance factor (ϕ) such that the distributions of R and Q will answer to the requirements of a specified β. In other words, the γ and ϕ described in Figure 3 need to answer to the prescribed target reliability (i.e. a predetermined probability of failure) described in Eq. (9). Several solutions are available and are described below, including the recommended procedure for the current research (part 1.3.5).

![Figure 3](image)

**Figure 3.** An illustration of the LRFD factors determination and application (typically γ ≥ 1, ϕ ≤ 1) relevant to the zone in which load is greater than resistance (Q > R).
Development of Resistance Factors

First Order Second Moment (FOSM)

The first AASHTO specifications were based on the First-Order, Second-Moment (FOSM) principles, assuming lognormal distribution for the resistance and bias factors, the following relations can be established (Barker et al., 1991).

\[
\phi = \frac{\lambda_R \left( \sum \gamma_i Q_i \right) \sqrt{1 + COV_Q^2}}{Q \exp \{ \beta_T \sqrt{\ln[(1 + COV_R^2)(1 + COV_Q^2)]} \}}
\]

where:
- \( \lambda_R \) = resistance bias factor
- \( COV_R \) = coefficient of variation of the resistance
- \( COV_Q \) = coefficient of variation of the load
- \( \beta_T \) = target reliability index

Considering dead and live loads only:

\[
\phi = \frac{\lambda_R \left( \frac{\gamma_D Q_D}{Q_L} + \gamma_L \right) \sqrt{\left[ \frac{(1 + COV_Q^2 + COV_R^2)}{1 + COV_R^2} \right]}}{\left( \frac{\lambda_QD Q_D}{Q_L} + \lambda_{QL} \right) \exp \{ \beta_T \sqrt{\ln[(1 + COV_R^2)(1 + COV_Q^2 + COV_{QL}^2)]} \}}
\]

where:
- \( \gamma_D, \gamma_L \) = dead and live load factors
- \( Q_D/Q_L \) = dead to live load ratio
- \( \lambda_{QD}, \lambda_{QL} \) = dead and live load bias factors
Monte Carlo Simulation – MCS

Monte Carlo Simulation (MCS) became the preferable calibration tool by AASHTO and is recommended for all AASHTO related calibrations. MCS is a powerful tool for determining the failure probability numerically, without the use of closed form solutions as those given by Equations 14 or 15. The objective of MCS is the numerical integration of the expression for failure probability, as given by the following equation.

\[ p_f = P(g \leq 0) = \frac{1}{N} \sum_{i=1}^{N} I[g_i \leq 0] \]  

(18)

where \( I \) is an indicator function which is equal to 1 for \( g_i \leq 0 \), i.e., when the resulting limit state is in the failure region, and equal to 0 for \( g_i > 0 \) when the resulting limit state is in the safe region; \( N \) is the number of simulations carried out. As \( N \to \infty \), the mean of the estimated failure probability using the above equation can be shown to be equal to the actual failure probability (Rubinstein, 1981).
Code calibration in its ideal format is accomplished in an iterative process by assuming agreeable load and resistance factors, $\gamma$’s and $\phi$’s, and determining the resultant reliability index, $\beta$. When the desired target reliability index, $\beta_T$, is achieved, an acceptable set of load and resistance factors has been determined. One unique set of load and resistance factors does not exist; different sets of factors can achieve the same target reliability index (Kulicki et al., 2007).

The MCS process is simple and can be carried out as follows:

- Identify basic design variables and their distributions. Load is assumed to be normally distributed.
- Generate $N$ number of random samples for each design variable based on their distributions, i.e. using the reported statistics of load and resistance and computer-generated random numbers.
- Evaluate the limit state function $N$ times by taking a set of the design variables generated above, and count the number for which the indicator function is equal to 1.
- If the sum of the indicator function is $N_f$, i.e., the limit state function was $g_i \leq 0$ (in the failure region) for $N_f$ number of times out of the total of $N$ simulations carried out, then the failure probability $p_f$ can be directly obtained as the ratio $N_f/N$. 
Using the MCS process, the resistance factor can be calculated based on the fact that to attain a target failure probability of $p_{IT}$, $N_{IT}$ samples of the limit state must fall in the failure region. Since in the present geotechnical engineering LRFD only one resistance factor is used, while keeping the load factors constant, a suitable choice of the resistance factor would shift the limit state function so that $N_{IT}$ samples fall in the failure region. The resistance factor derived in this study using MCS is based on this concept.

Kulicki et al. (2007) made several observations regarding the above outlined process:

1. The solution is only as good as the modeling of the distribution of load and resistance. For example, if the load is not correctly modeled or the actual resistance varies from the modeled distribution, the solution is not accurate, i.e. if the statistical parameters are not well defined, the solution is equally inaccurate.

2. If both the distribution of load and resistance are assumed to be normally or lognormally distributed, Monte Carlo simulation using these assumptions should theoretically produce the same results as the closed-form solutions.

3. The power of the Monte Carlo simulation is its ability to use varying distributions for load and resistance.

In summary, refinement in the calibration should be pursued not in refining the process used to calculate the reliability index; the Monte Carlo simulation as discussed above is quite adequate and understandable to the practicing engineer. Refinement should be sought in the determination of the statistical parameters of the various components of force effect and resistance and using the load distributions available for the structural analysis, this means focusing on the statistical parameters of the resistance.
3 LRFD DESIGN
RBD for Foundations

All existing codes suffer from two major difficulties:

1. The application of RBD to geotechnical problems (e.g. site variability, construction effects, past experience, etc.) – Detailed Framework developed for the current Eurocode 7 (2004).

2. Lack of data. None of the reviewed codes and associated resistance factors were developed based on databases enabling the calculation of resistance factors from case histories. The existing factors are either back calculated from factors of safety, based on incomplete related data, based on judgment, or a combination of the above.
An extensive development of resistance factors for the AASHTO specifications of Deep Foundations was undertaken under NCHRP project 24-17 and presented in NCHRP Report 507. These factors were developed based on large databases examining the deep foundations capacity prediction methods during design and construction.

Google Search: NCHRP 507 will bring you to the pdf
3 LRFD DESIGN
Framework For The Development Of The Resistance Factors In NCHRP 507

REQUIRED INFORMATION
- Distribution of Load - Type, Mean, SD
- Distribution of Resistance – Type, Mean, SD
- Probability of Failure

POSSIBLE SOURCES
- Distribution of Load – Measurements on and Analyses of Structures – e.g. Vehicles on a Bridge
- Distribution of Resistance – Databases, Related Correlations - e.g. Soil Parameters, Judgment
- Probability of Failure – Observations, Judgment, Probabilistic Theory
# Required And Sources Of Information

<table>
<thead>
<tr>
<th>Required Information</th>
<th>Sources of Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Combination</td>
<td>AASHTO Strength I DL &amp; LL</td>
</tr>
<tr>
<td>Load Factors</td>
<td>( \gamma_D = 1.25 ) ( \gamma_L = 1.75 )</td>
</tr>
<tr>
<td>Distribution of Load</td>
<td>Type Lognormal</td>
</tr>
<tr>
<td></td>
<td>Mean ( \lambda_{QD} = 1.05 ) ( \lambda_{QL} = 1.15 )</td>
</tr>
<tr>
<td></td>
<td>COV ( \text{COV}<em>{QD} = 0.1 ) ( \text{COV}</em>{QL} = 0.2 )</td>
</tr>
<tr>
<td>Nature of Resistance</td>
<td>Geotechnical – Axial resistance</td>
</tr>
<tr>
<td>Distribution of Resistance</td>
<td>Database Analysis</td>
</tr>
<tr>
<td>Probability of Failure</td>
<td>Review Available Literature/Develop</td>
</tr>
</tbody>
</table>
Main Analyses:
- Driven Piles Static Analyses - 527 piles
- Drilled Shafts Static Analyses - 300 shafts
- Driven Piles Dynamic Analyses - 389 cases on 210 piles

Peripheral Analyses:
- Static Load Test Interpretation DP - 196 piles
- Static Load Test Interpretation DS - 44 shafts
- Influence of Loading Rate - 75 piles
- Dynamic Measurements both EOD & BOR (without Static Load Test) - 456 cases on 228 piles
- WEAP (GRL Database) - 99 piles
- Case Method (Florida Study): EOD - 40 piles
  BOR - 37 piles
3 LRFD DESIGN

Calculated Resistance Factors

• Target Reliability

(probability of exceedance = Probability of failure)

• Efficiency Factor
3 LRFD DESIGN
Redundant vs. Non–Redundant

NCHRP 507 Recommendations

- Redundant: $\beta = 3.00$, $P_f = 0.1\%$
- Non-Redundant: $\beta = 2.33$, $P_f = 1.0\%$

Logically
Non-Redundant

Redundant
3 LRFD DESIGN
Design Method Efficiency
Resistance Factor Over Bias- $\phi/\lambda_v$

Figure 15. Calculated resistance factors as a function of the bias and COV for the chosen load distributions and DD/LL ratio of 2.5

Figure 16. Illustration of the efficiency factor as a measure of the effectiveness of a design method when using resistance factors.
3 LRFD DESIGN
Example of Code Calibration – ULS

- Static Analyses Driven Piles
- Dynamic Analyses Driven Piles
- Case History
Figure 7. Histogram and frequency distribution of measured over statically calculated pile capacities for 146 cases of all pile types (concrete, pipe, H) in mixed soil (Paikowsky et al., 2004).
Table 25. Recommended resistance factors for driven piles static analyses

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Soil Type</th>
<th>Design Method</th>
<th>Redundant</th>
<th>Non-redundant</th>
<th>Redundant</th>
<th>Non-redundant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Pile</td>
<td>Mixed</td>
<td>SPT97 mob</td>
<td>0.70</td>
<td>0.50</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>Sand</td>
<td>Clay</td>
<td>α-API</td>
<td>0.50</td>
<td>0.40</td>
<td>0.46</td>
<td>0.34</td>
</tr>
<tr>
<td>Mixed</td>
<td>β-Method/Thurman</td>
<td>SPT97 mob</td>
<td>0.40</td>
<td>0.30</td>
<td>0.51</td>
<td>0.39</td>
</tr>
<tr>
<td>Sand</td>
<td>Nordlund</td>
<td>α-Tomlinson/Nordlund/Thurman</td>
<td>0.35</td>
<td>0.25</td>
<td>0.41</td>
<td>0.30</td>
</tr>
<tr>
<td>Pipe Pile</td>
<td>Mixed</td>
<td>α-API/Nordlund/Thurman</td>
<td>0.20</td>
<td>0.15</td>
<td>0.41</td>
<td>0.30</td>
</tr>
<tr>
<td>Sand</td>
<td>Meyerhof</td>
<td>α-Tomlinson</td>
<td>0.25</td>
<td>0.15</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>Mixed</td>
<td>α-API/Nordlund/Thurman</td>
<td>SPT 97 mob</td>
<td>0.45</td>
<td>0.35</td>
<td>0.51</td>
<td>0.39</td>
</tr>
<tr>
<td>Sand</td>
<td>Meyerhof</td>
<td>α-Tomlinson</td>
<td>0.36</td>
<td>0.26</td>
<td>0.41</td>
<td>0.30</td>
</tr>
<tr>
<td>Mixed</td>
<td>β-Method/Thurman</td>
<td>α-Tomlinson</td>
<td>0.25</td>
<td>0.15</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>Clay</td>
<td>β-Method/Thurman</td>
<td>λ-Method</td>
<td>0.36</td>
<td>0.25</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>H Piles</td>
<td>Mixed</td>
<td>SPT 97 mob</td>
<td>0.55</td>
<td>0.45</td>
<td>0.45</td>
<td>0.33</td>
</tr>
<tr>
<td>Sand</td>
<td>SPT 97 mob</td>
<td>Nordlund</td>
<td>0.45</td>
<td>0.35</td>
<td>0.49</td>
<td>0.37</td>
</tr>
<tr>
<td>Clay</td>
<td>Meyerhof</td>
<td>λ-Method</td>
<td>0.40</td>
<td>0.30</td>
<td>0.49</td>
<td>0.37</td>
</tr>
<tr>
<td>Mixed</td>
<td>λ-Method/Thurman</td>
<td>α-API</td>
<td>0.35</td>
<td>0.25</td>
<td>0.45</td>
<td>0.34</td>
</tr>
<tr>
<td>Sand</td>
<td>β-Method/Thurman</td>
<td>α-Tomlinson/Nordlund/Thurman</td>
<td>0.30</td>
<td>0.25</td>
<td>0.51</td>
<td>0.39</td>
</tr>
<tr>
<td>Mixed</td>
<td>β-Method/Thurman</td>
<td>λ-Method</td>
<td>0.20</td>
<td>0.15</td>
<td>0.42</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Notes:
- Non-Redundant = Four or less piles under one pile cap (β = 3.0 pf = 0.1%)
- Redundant = Five piles or more under one pile cap (β = 2.33 pf = 1.0%)
- λ = bias = Mean KSX = measured/predicted
- φ/λ = efficiency factor, evaluating the relative economic performance of each method (the higher the better)
- φ/λ values relate to the exact calculated φ and λ, and not to the assigned φ values in the table

3/19/02 7/11/02 7/15/02
Figure 6. Histogram and Frequency Distributions for all (377 cases) Measured over Dynamically (CAPWAP) Calculated Pile-Capacities in PD/LT2000 (Paikowsky et al., 2004).
Histogram & Frequency Distributions for all BOR (162) CAPWAP pile-cases in PD/LT2000

3 LRFD DESIGN
Example of Code Calibration – ULS

Ratio of Static Load Test Results over the Pile Capacity Prediction using the CAPWAP method

Log-normal distribution
$m_n = 0.100$
$c_n = 0.295$

Normal distribution
$m = 1.158$
$\sigma = 0.393$

Number of Pile-Cases

Relative Frequency
Histogram & Frequency Distributions for all (371) Energy Approach pile-cases in PD/LT2000

Ratio of Static Load Test Results over the Pile Capacity Prediction using the Energy Approach method

log-normal distribution
\[ \ln x = -0.187 \]
\[ \sigma_{\ln x} = 0.379 \]

normal distribution
\[ m_x = 0.894 \]
\[ \sigma_x = 0.367 \]
3 LRFD DESIGN

Recommended resistance factors
Driven Piles – Dynamic Analyses

Table 27. Recommended resistance factors for driven piles dynamic analyses

<table>
<thead>
<tr>
<th>Method</th>
<th>Case</th>
<th>Resistance factor, $\phi$</th>
<th>$\phi / \lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Redundant</td>
<td>Non-Redundant</td>
</tr>
<tr>
<td>Dynamic Measurements</td>
<td>EOD</td>
<td>0.65</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>EOD, AR&lt;350, Bl. Ct.&lt;16BP10cm</td>
<td>0.40</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>BOR</td>
<td>0.65</td>
<td>0.50</td>
</tr>
<tr>
<td>Dynamic Equations</td>
<td>EOD</td>
<td>0.55</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>BOR</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>ENR</td>
<td>General</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Gates</td>
<td>General</td>
<td>0.75</td>
<td>0.55</td>
</tr>
<tr>
<td>FHWA modified</td>
<td>General</td>
<td>0.40</td>
<td>0.25</td>
</tr>
<tr>
<td>WEAP</td>
<td>EOD</td>
<td>0.40</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Notes: $\beta$ = Reliability Index  $p_f = Probability of Failure  COV = Coefficient of Variation
EOD = End of Driving  BOR = Beginning of Restrike  Bl. Ct. = Blow Count
AR = Area Ratio  ENR = Engineering News Record Equation
BP10cm = Blows per 10cm  Non-Redundant= Four or less piles under one pile cap ($\beta = 3.0 \ p_f = 0.1\%$)
Redundant = Five piles or more under one pile cap. ($\beta = 2.33 \ p_f = 1.0\%$)  $\lambda$ = bias = Mean $K_{sx}$ = measured/predicted
$\phi / \lambda$ = efficiency factor, evaluating the relative economic performance of each method (the higher the better)
$\phi / \lambda$ values relate to the exact calculated $\phi$ and $\lambda$ and not to the assigned $\phi$ values in the table.
### Table 30. Recommended resistance factors for static load tests

<table>
<thead>
<tr>
<th>No. of Load Tests Per Site</th>
<th>Site Variability</th>
<th>Resistance Factor - $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
</tr>
<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>
</tr>
<tr>
<td>3</td>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td>$\geq$ 4</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>
### 3 LRFD DESIGN

#### Recommended Number of Pile Tests During Production

Table 28. Recommended number of dynamic tests to be conducted during production

<table>
<thead>
<tr>
<th>Site Var.</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Piles</td>
<td>Method</td>
<td>EA</td>
<td>CAPWAP</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>EOD</td>
<td>BOR</td>
</tr>
<tr>
<td>≤ 15</td>
<td>EOD</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>16 - 25</td>
<td></td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>26 - 50</td>
<td></td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>51 – 100</td>
<td></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>101-500</td>
<td></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>&gt; 500</td>
<td></td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

EA = Energy Approach Analysis  
CAPWAP = Signal Matching Analysis  
EOD = End of Driving  
BOR = Beginning of Restrike  
Minimum one test under each substructure
Site Variability Assessment - Example

Area A (4 borings)

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>n</th>
<th>$m_x$</th>
<th>$\sigma_x$</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>10</td>
<td>8.1</td>
<td>81%</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2</td>
<td>2.1</td>
<td>128%</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>18</td>
<td>5.0</td>
<td>28%</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>19</td>
<td>4.8</td>
<td>25%</td>
</tr>
</tbody>
</table>

n – Number of Values

Variability

- High
- High
- Low-Med
- Low
7 SUMMARY OF LECTURE 6
1. USA WSD Practice recommends F.S. = 3.0 for B.C. calculations and SLS examination.

2. Factors of safety or other safety margins can be examined or explained only on the basis of actual data.

3. Codes worldwide are transforming to RBD.

4. The new AASHTO specifications (when viewed in a broad perspective) represents a major advance in design worldwide and is the most enhanced platform for a true RBD code based on actual data performance.

5. Comprehensive LRFD factors for deep foundations are presented in NCHRP Research Report 507. These factors are based on the controlling parameters of the design and construction methods. The study used databases allowing to evaluate the actual performance of the different capacity prediction methods; both in design and construction.
6. The NCHRP study calibrated a “complete” design methodology including soil parameter correlations. The use of the recommended resistance factors is associated therefore with a specific design methodology for the static evaluation (design stage) and category during the construction stage; (e.g. time and blow count for applying dynamic analyses and site variability for static load tests).

You cannot mix factors – e.g Using construction phase RF with static analysis calculations just because you intend to run a static LT or dynamic tests.
The attempt of the current AASHTO specifications to “simplify” the RF recommended by NCHRP 507 can be dangerous!

“Everything should be made as simple as possible, but not simpler” ....... (A. Einstein)

Conclusions – follow closely the specifications and the RF recommended by NCHRP 507
8. The examination of either factors of safety or resistance factors on the basis of their absolute values is misleading and efficiency factors ($\phi/\lambda$ or $FSx\lambda$) are required to represent the economical value of a specific method.

9. When developing resistance factors based on actual databases one faces the difficulties of comparisons with existing factors which are questionable to begin with.

10. Consistent level of reliability means that some methods of analysis become more conservative while others become less conservative.