14.533 - Advanced Foundation Engineering

Lecture 6 - Standards and Reliability Based Design

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1 DESIGN PRACTICE

Codes in the USA

- 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:

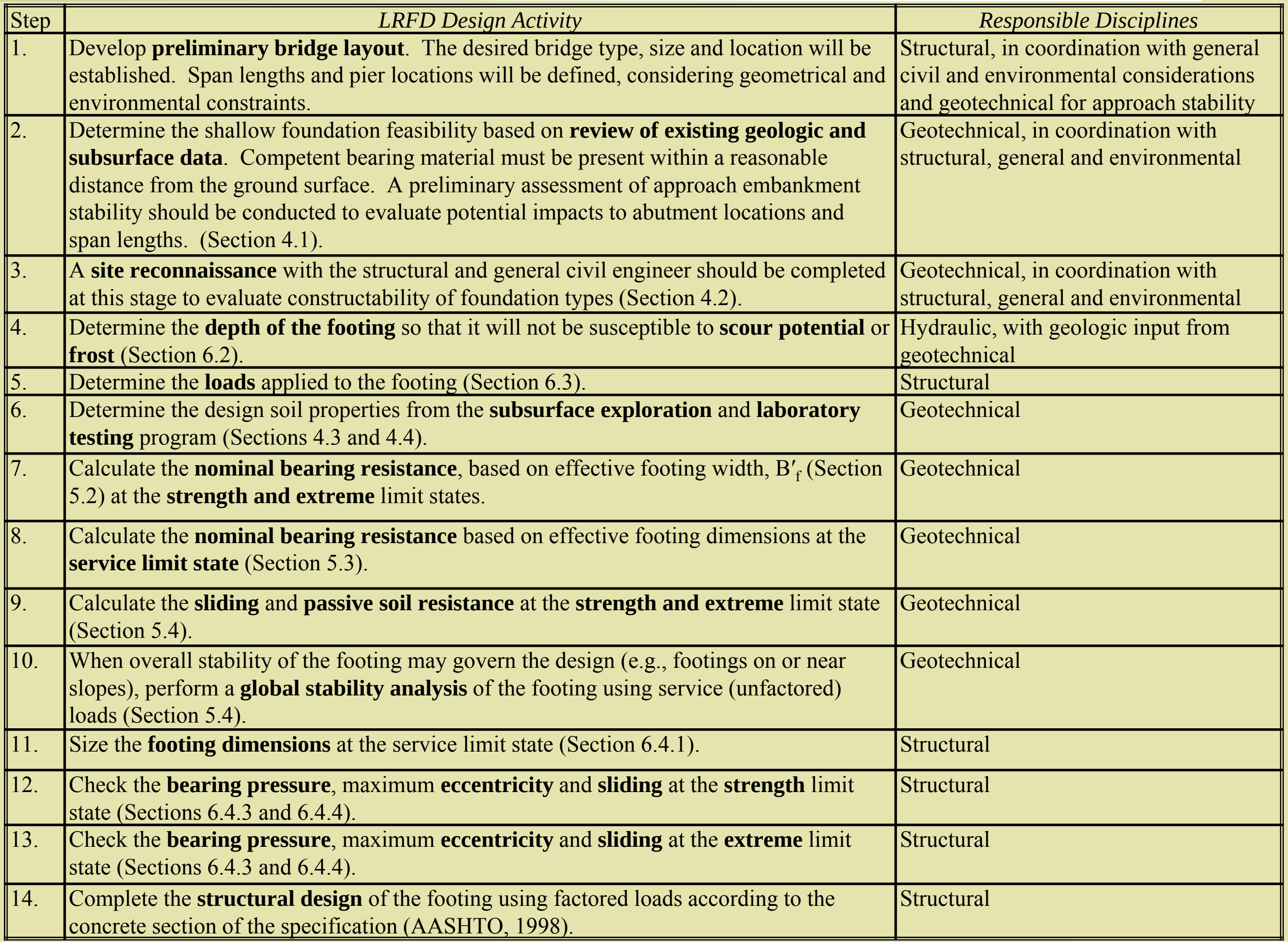
By and large design of shallow foundations on soils is controlled by SLS and design of shallow foundations on rock by SLS. IGM's can go either way depending on density and cementation

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

Kimmerling,R.E. (2002). Geotechnical Engineering Circular No. 6 Shallow Foundations, FHWA-IF-02-054, FHWA, Washington, DC.



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

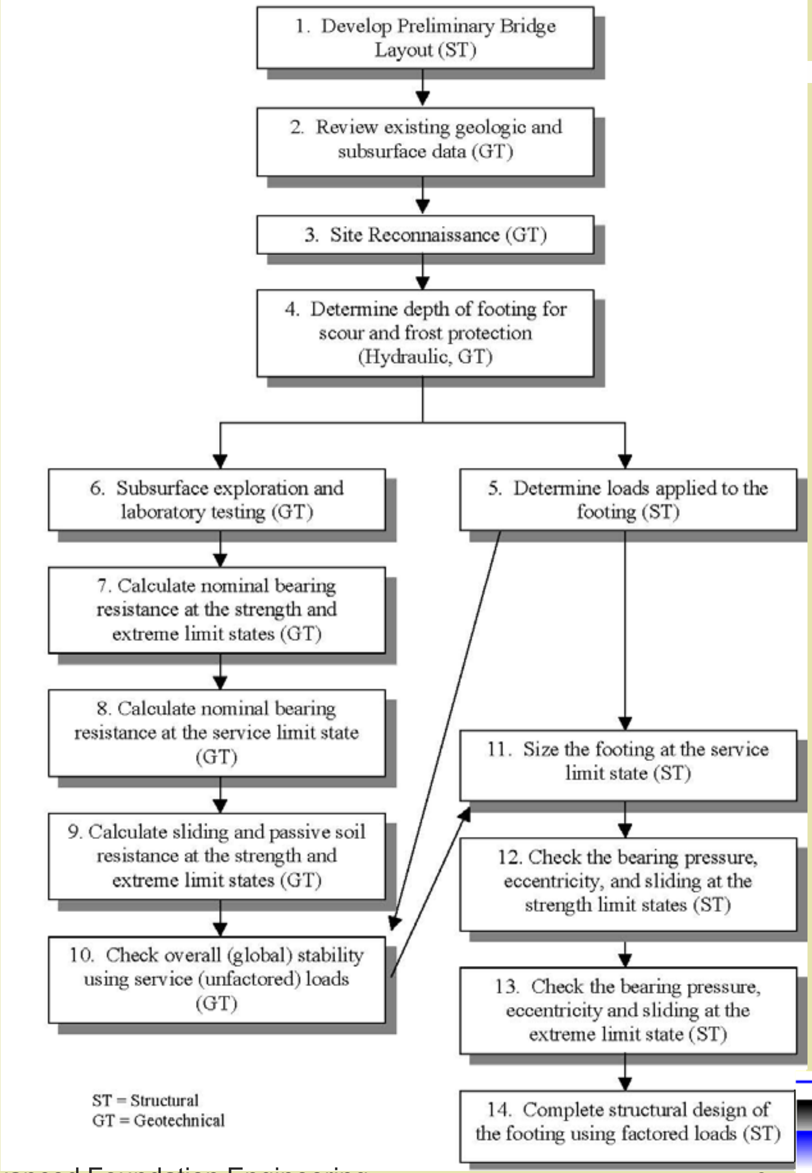
1 DESIGN PRACTICE

Shallow Foundations

Design Process

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

Kimmerling,R.E. (2002). Geotechnical Engineering Circular No. 6 Shallow Foundations, FHWA-IF-02-054, FHWA, Washington, DC.



1. Develop Preliminary Bridge Layout (ST)
2. Review existing geologic and subsurface data (GT)
3. Site Reconnaissance (GT)
4. Determine depth of footing for scour and frost protection (Hydraulic, GT)
5. Determine loads applied to the footing (ST)
6. Subsurface exploration and laboratory testing (GT)
7. Calculate nominal bearing resistance at the strength and extreme limit states (GT)
8. Calculate nominal bearing resistance at the service limit state (GT)
9. Calculate sliding and passive soil resistance at the strength and extreme limit states (GT)
10. Check overall (global) stability using service (unfactored) loads (GT)
11. Size the footing at the service limit state (ST)
12. Check the bearing pressure, eccentricity, and sliding at the strength limit states (ST)
13. Check the bearing pressure, eccentricity and sliding at the extreme limit state (ST)
14. Complete structural design of the footing using factored loads (ST)

ST = Structural
GT = Geotechnical

2 DESIGN METHODOLOGIES

2 DESIGN METHODOLOGIES

Review – Working Stress Design

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.**

$$Q \leq Q_{all} = R_n / FS = Q_{ult} / FS$$

Q = **Design load (F)**

Q_{all}= **Allowable load (F)**

R_n= Q_{ult} = **Nominal Resistance = Ultimate geotechnical pile force resistance**

FS = **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

Factor Of Safety On Ultimate Pile Axial Geotechnical Capacity Based On Specified Construction Control (AASHTO 1997 Standard Specifications)

X - Construction Control Specified on Plans	Increasing Construction Control				
Subsurface Exploration	X	X	X	X	X
Static Calculation	X	X	X	X	X
Dynamic Formula	X				
Wave Equation		X	X	X	X
CAPWAP Analysis			X		X
Static Load Test				X	X
Factor of Safety (FS)	**3.50**	**2.75**	**2.25**	**2.00***	**1.90**

* Any combination that includes a static load test

Design Capacities Specified on Plans so FS can be Adjusted if Construction Control is Altered

2 DESIGN METHODOLOGIES
Review - Working Stress Design

Comments

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.

2 DESIGN METHODOLOGIES

Review - Working Stress Design

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)

Capacity Evaluation Method	F.S.	Load per Pile (tons)	# of Piles	Savings
Static Analysis	3.50	28.6	7.0	-
WEAP	2.75	36.4	5.5	- 21%
CAPWAP	2.25	44.4	4.5	- 36%
Static L.T.	2.00	50.0	4.0	- 43%

2 DESIGN METHODOLOGIES

Review - Working Stress Design

Evaluation of Parameters - Driven Piles In Clay

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

Pile Type	Method					
	α API		α Tomlinson		λ	
Concrete	17	0.81	18	0.87	18	0.76
Pipe	19	0.79	18	0.64	19	0.67
H	16	0.90	17	0.82	16	0.74
Total	52	0.83	51	0.81	53	0.72

(1/0.8 = 1.25)

Actual Mean FS for driven piles in clay

α Methods = 0.82 x 3.5 = **2.87**
λ Method = 0.72 x 3.5 = **2.52**

For Comparison – FS for the Dynamic Methods
CAPWAP - BOR 162 Mean = 1.16

Actual FS BOR = 1.16 x 2.25 = **2.61**

2 DESIGN METHODOLOGIES

Review - Working Stress Design

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)

Capacity Evaluation Method	F.S. (Load)	Load per Pile - ton (w/o bias)	# of Piles (w/o bias)	Savings (w/o bias)
Static Analysis α API Clay	3.50 on 123t	35.3 (28.6)	5.7 (7)	-
WEAP EOD	2.75 on 60t	22.0 (36.4)	9.1 (5.5)	+60% (-21%)
CAPWAP BOR	2.25 on 86t	38.4 (44.4)	5.2 (4.5)	-9% (-36%)
Static L.T.	2.00 on100t	50.0	4.0	-30% (-43%)

(values in original example ignoring the bias)

2 DESIGN METHODOLOGIES

Review - Working Stress Design

INTERMEDIATED CONCLUSION

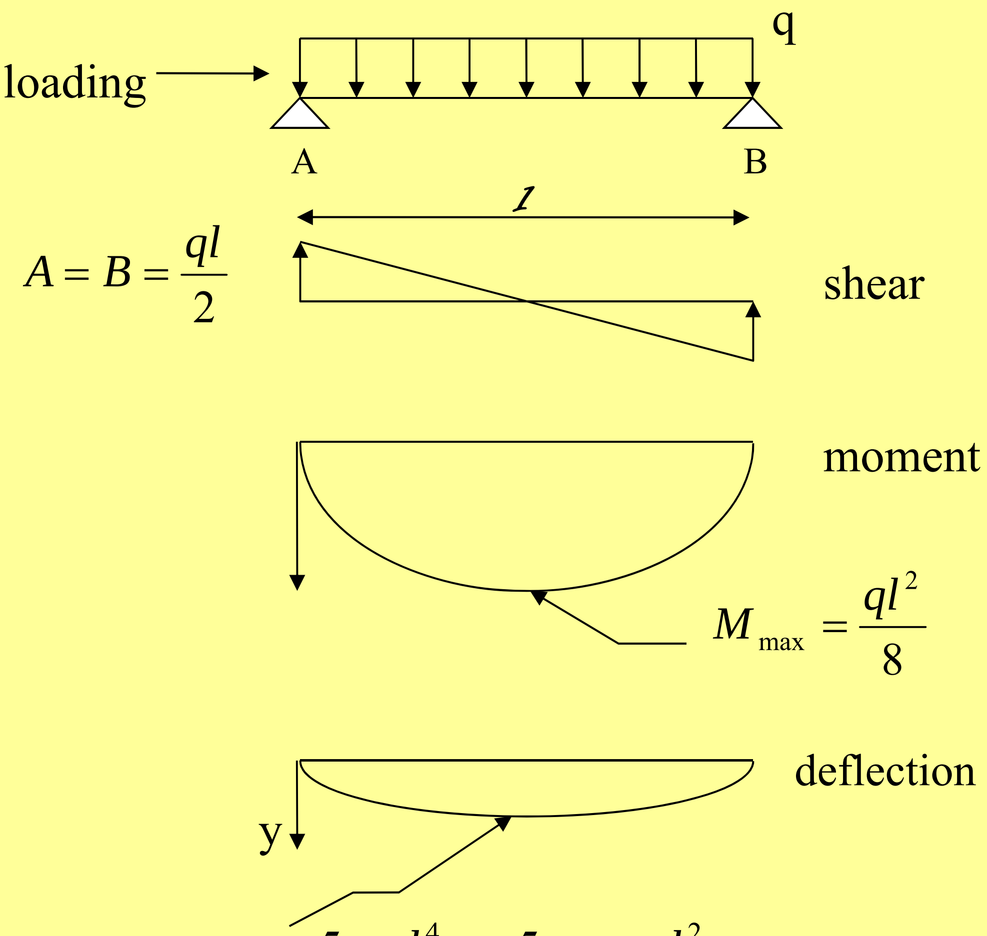
1. The examination of factors of safety on the basis of their absolute values is misleading and do not represent the economical value of a specific method.

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



$$A = B = \frac{ql}{2}$$

$$M_{\max} = \frac{ql^2}{8}$$

$$y_{\max} = \frac{5}{384}\frac{ql^4}{EI} = \frac{5}{24}\frac{\sigma_{\max}}{E}\frac{l^2}{h}$$

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

- **Sources of Uncertainty**
  1. Loading
  2. Dimensions
  3. Material Properties

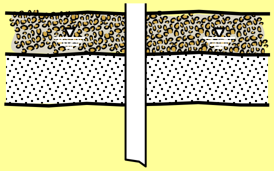
- **Most Noticeable:**

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)

Uncertainties - Geotechnical Design

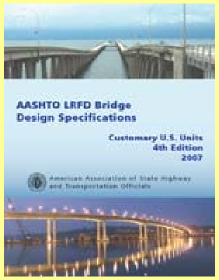
Components of Foundations Design and Sources of Uncertainty

Soil sampling and testing for engineering material parameters



Uncertainty due to site, material and testing variability and estimation of parameters

Code of practice



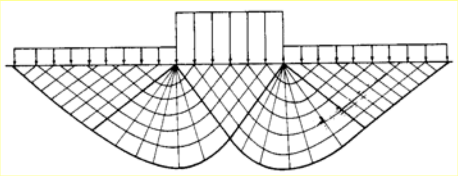
AASHTO LRFD Bridge Design Specifications

Customary U.S. Units
4th Edition
2007

American Association of State Highway and Transportation Officials

Traditional design although developed over many years and used as a benchmark has undocumented unknown uncertainty

Analysis Model



Assumed Failure Pattern under Foundations

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

FOUNDATION DESIGN

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.

Loading

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

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)

3 LRFD DESIGN

LRFD for Foundations

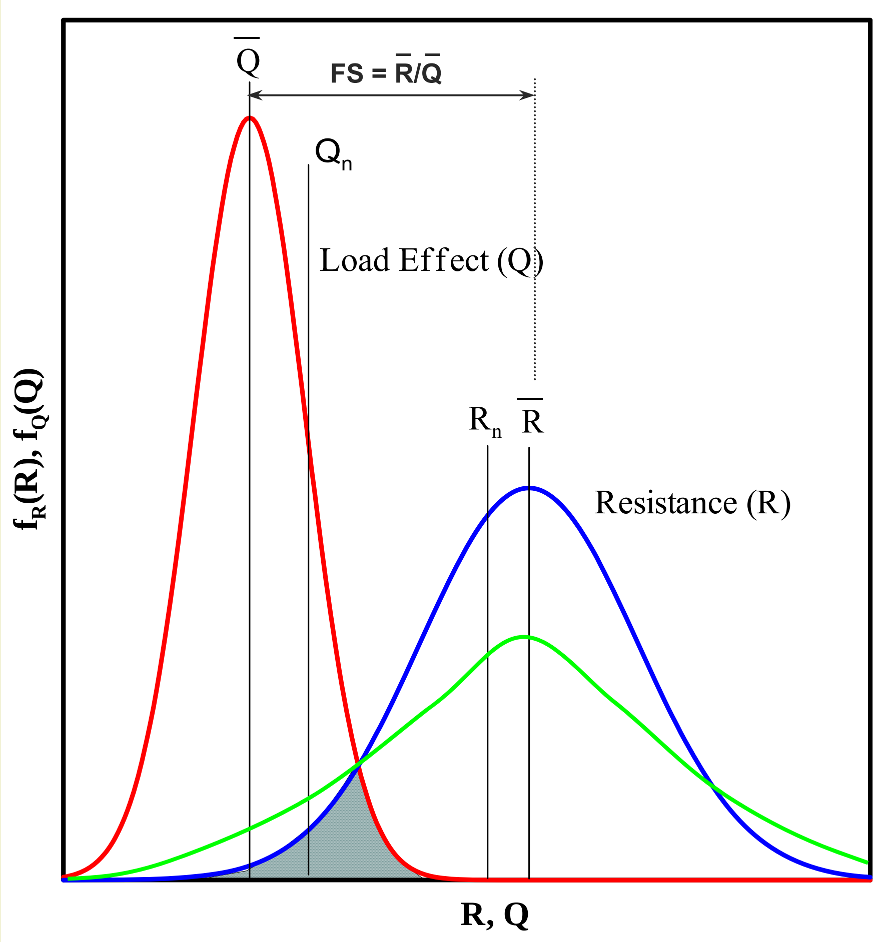
Principles

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



Q, R – Mean Load/Resistance

Q_n, R_n – Nominal Load/Resistance

consistent levels of reliability

An illustration of probability density functions for load effect and resistance

3 LRFD DESIGN

Probability of Failure

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);

$$g = R - Q \qquad (4)$$

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;

$$p_f = P(g < 0) \qquad (5)$$

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”, β. 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;

$$\beta = m_g / \sigma_g = \left(m_R - m_Q\right) \Big/ \sqrt{\sigma_Q^2 + \sigma_R^2} \qquad (6)$$

where m_g, σ_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

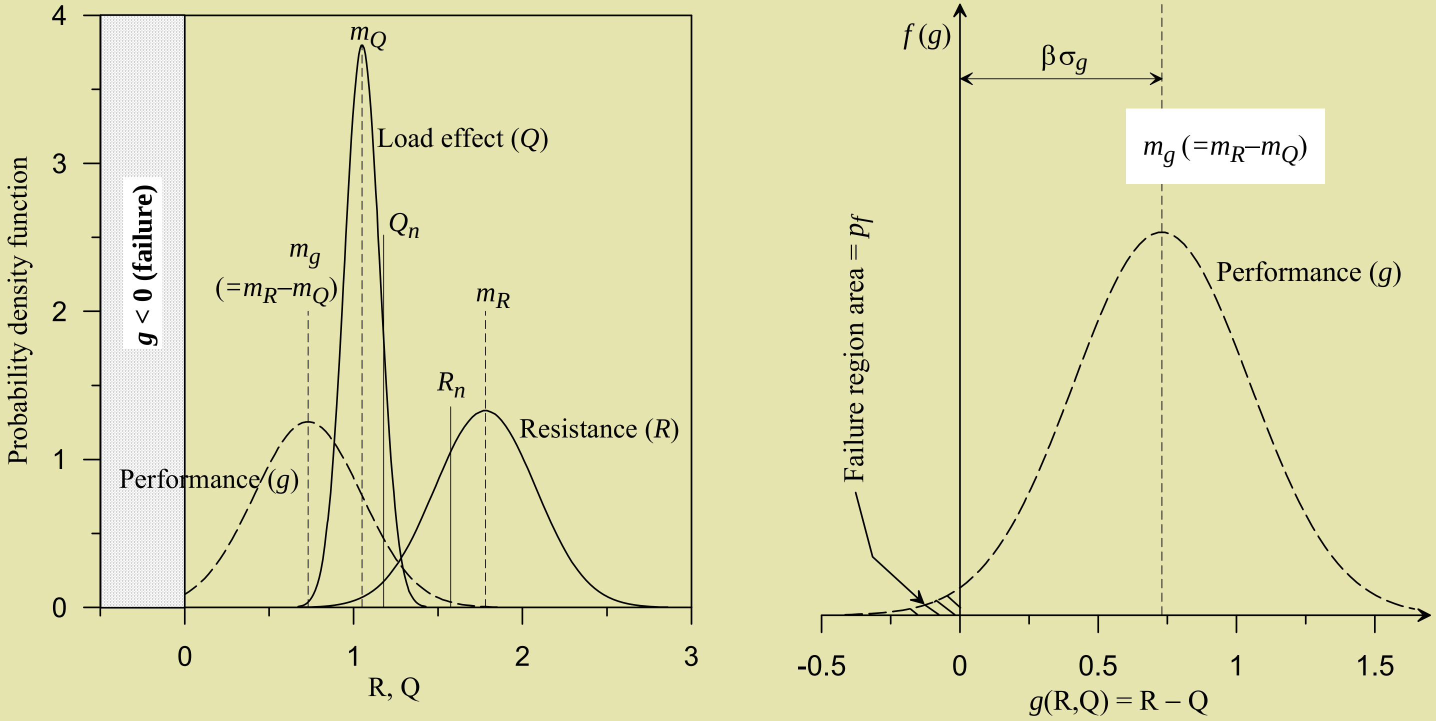


Figure 2. An illustration of probability density function for (a) load, resistance and performance function, and (b) the performance function (g(R,Q)) demonstrating the margin of safety (p_f) and its relation to the reliability index β. (σ_g = standard deviation of g).

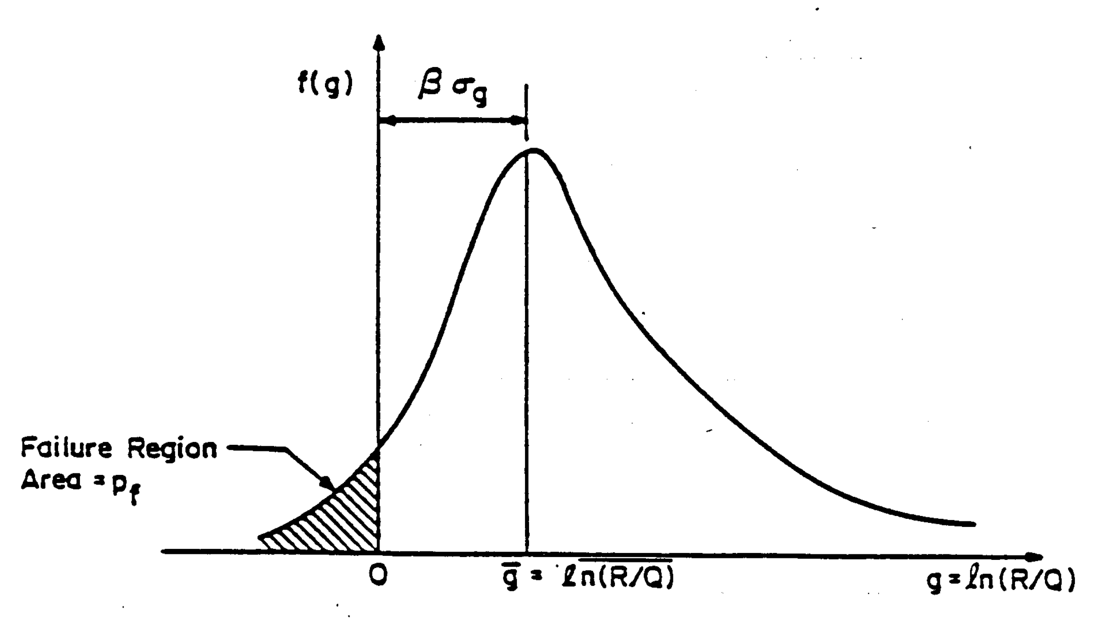
3 LRFD DESIGN

Target Reliability – Probability of Failure

Relationship Between Reliability Index and Target Reliability

Reliability Index β	Probability of Failure p_f
1.0	0.159
1.2	0.115
1.4	0.0808
1.6	0.0548
1.8	0.0359
2.0	0.0228
2.2	0.0139
2.4	0.00820
2.6	0.00466
2.8	0.00256
3.0	0.00135
3.2	6.87 E^{-4}
3.4	3.37 E^{-4}
3.6	1.59 E^{-4}
3.8	7.23 E^{-5}
4.0	3.16 E^{-5}

Reliability is expressed using the "reliability index", β, 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, β (σg = Standard Deviation of g).

3 LRFD DESIGN FOR FOUNDATIONS

1994, 1st. AASHTO LRFD Bridge Design Specs for Foundations

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);

ϕ = Resistance factor (dimensionless);

R_n = Nominal (Ultimate) resistance (F or F/A);

η = Factors to account for ductility (η_D), redundancy (η_R), and operational importance (η_I) – Structural (dimensionless)

γ_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)

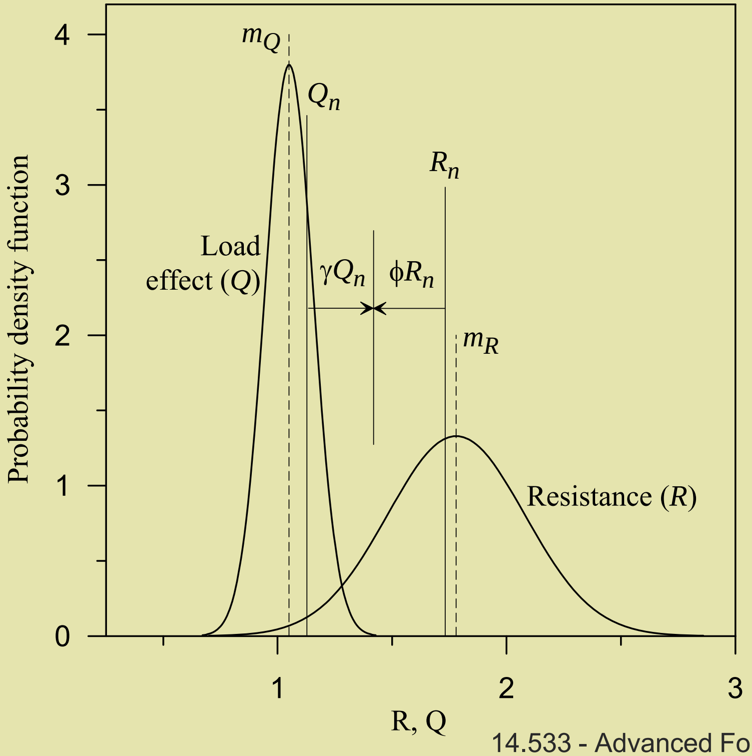


Figure 3. An illustration of the LRFD factors determination and application (typically $\gamma \geq 1$, $\phi \leq 1$) relevant to the zone in which load is greater than resistance (Q > R).

3 LRFD DESIGN
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).

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

where:

λ_R = resistance bias factor

COV_R = coefficient of variation of the resistance

COV_Q = coefficient of variation of the load

β_T = target reliability index

Considering dead and live loads only:

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

where: γ_Δ, γ_L dead and live load factors

Q_D/Q_L dead to live load ratio

$\lambda_{Q\Delta}$, λ_{QL} dead and live load bias factors

3 LRFD DESIGN

Development of Resistance 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.

$$p_f = P(g \leq 0) = \frac{1}{N} \sum_{i=1}^{N} I[g_i \leq 0] \tag{18}$$

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).

3 LRFD DESIGN

Methods of Calibration – MCS

Code calibration in its ideal format is accomplished in an iterative process by assuming agreeable load and resistance factors, γ's and ϕ's, and determining the resultant reliability index, β. When the desired target reliability index, β_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.

3 LRFD DESIGN

Methods of Calibration – MCS

Using the MCS process, the resistance factor can be calculated based on the fact that to attain a target failure probability of p_{fT} , N_{fT} 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_{fT} 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.**

3 LRFD DESIGN

NCHRP Report 507 Deep Foundations Design

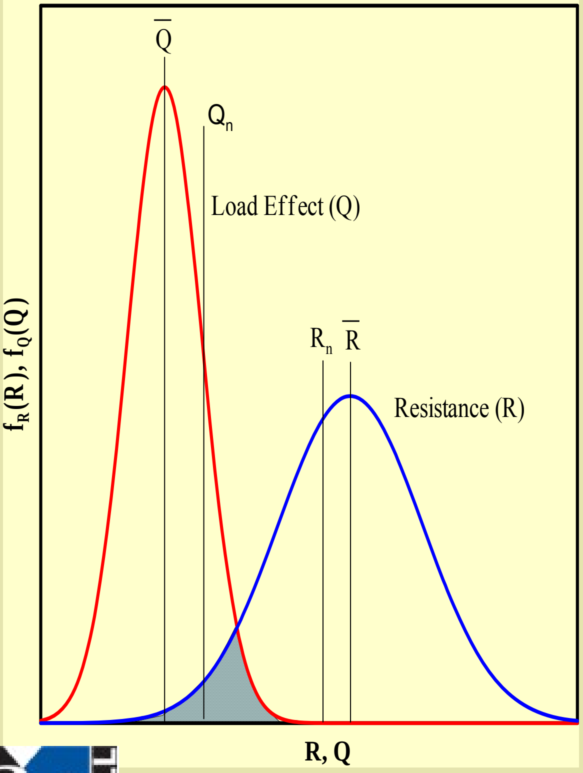
An extensive development of resistance factors for the AASHTO specifications of Deep Foundations was undertaken under NCHRP project 24-17 and presented in NCHRP Report 507. These factors were developed based on large databases examining the deep foundations capacity prediction methods during design and 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

$$R_r = \phi R_n \geq \sum \gamma_i Q_i$$



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

3 LRFD DESIGN

Framework For Calibration

Required And Sources Of Information

Required Information		Sources of Information
Load Combination		AASHTO Strength I DL & LL
Load Factors		$\gamma_D = 1.25$ $\gamma_L = 1.75$
Distribution of Load	Type	Lognormal
	Mean	$\lambda_{QD} = 1.05$ $\lambda_{QL} = 1.15$
	COV	$COV_{QD} = 0.1$ $COV_{QL} = 0.2$
Nature of Resistance		Geotechnical – Axial resistance
Distribution of Resistance		Database Analysis
Probability of Failure		Review Available Literature/Develop

3 LRFD DESIGN

Databases

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

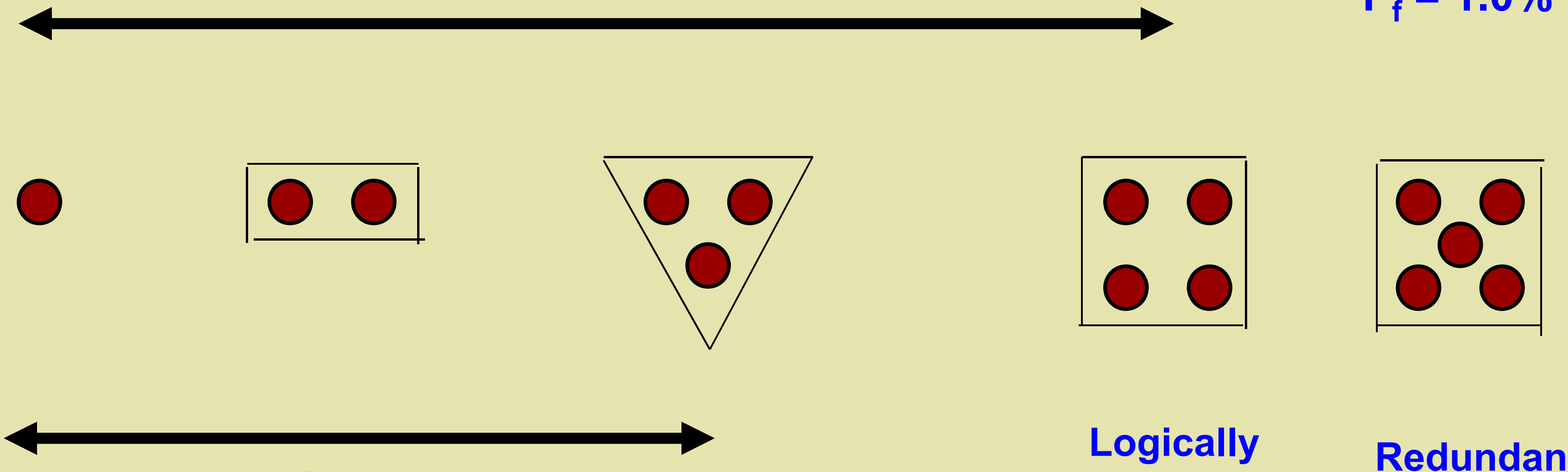
- **Target Reliability**

  (probability of exceedance = Probability of failure)

- **Efficiency Factor**

3 LRFD DESIGN
Redundant vs. Non–Redundant

NCHRP 507 Recommendations



$\beta = 3.00$ $P_f = 0.1\%$

$\beta = 2.33$
$P_f = 1.0\%$

Non - Redundant

Logically

Non - Redundant

Redundant

3 LRFD DESIGN

Design Method Efficiency

Resistance Factor Over Bias- ϕ/λ_v

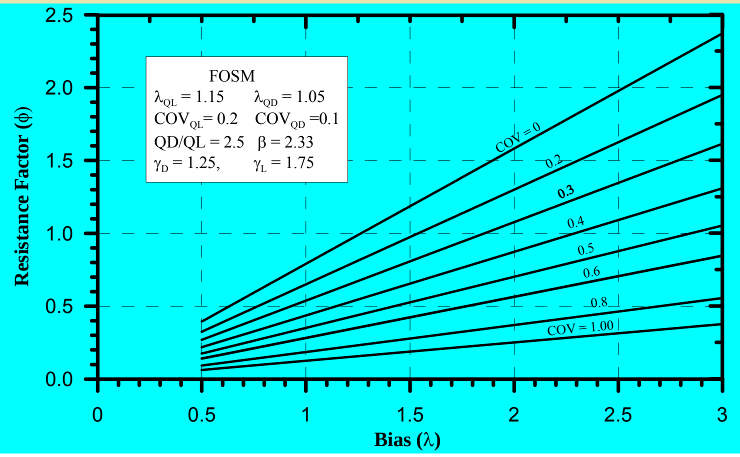


Figure 15. Calculated resistance factors as a function of the bias and COV for the chosen load distributions and DD/LL ratio of 2.5

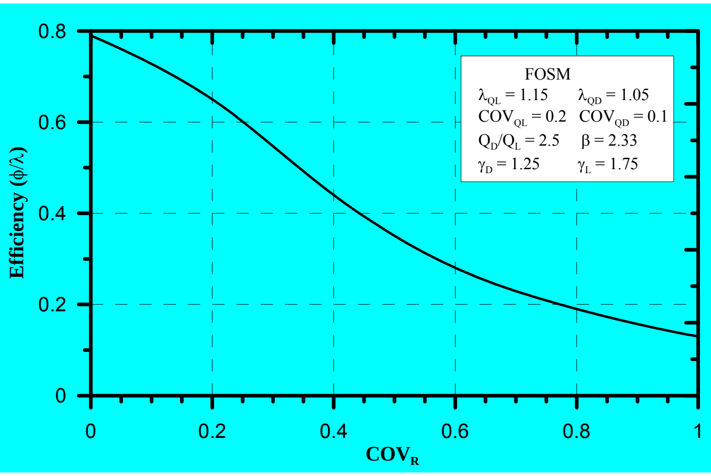


Figure 16. Illustration of the efficiency factor as a measure of the effectiveness of a design method when using resistance factors.

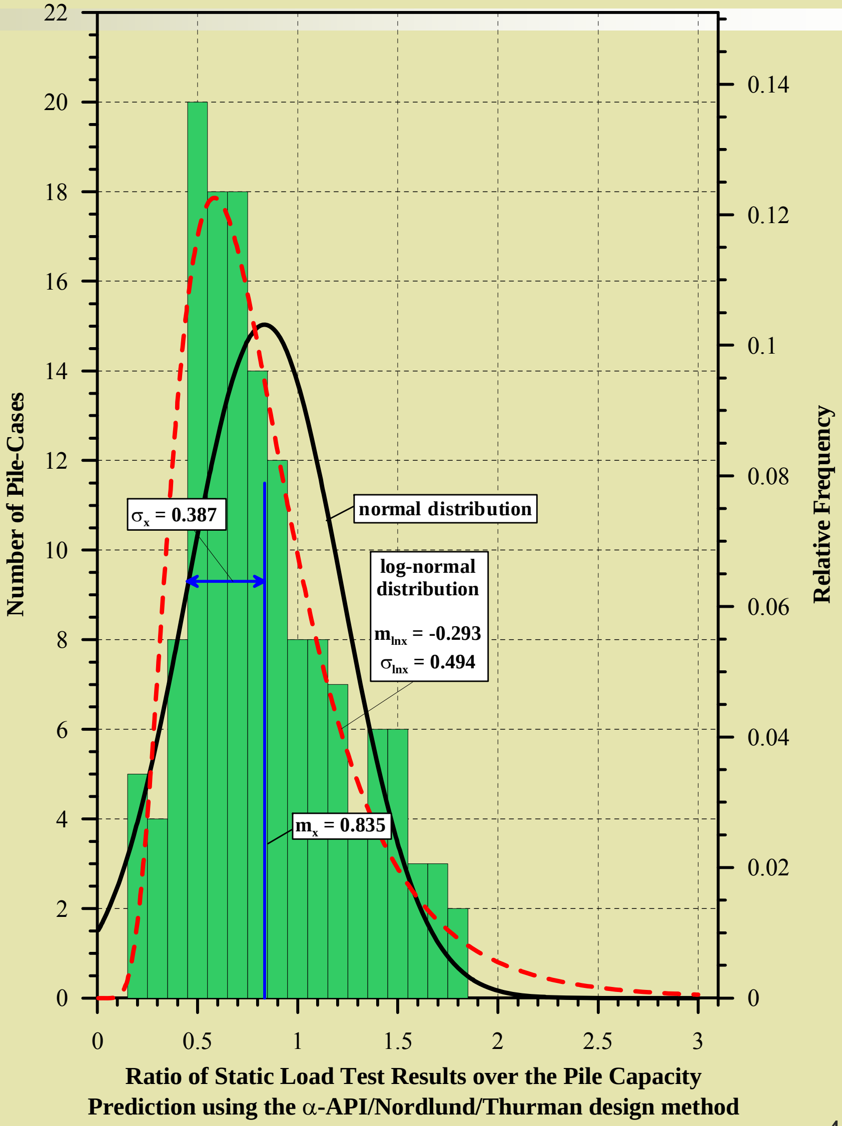
Efficiency-Resistance factor.grf

3 LRFD DESIGN
Example of Code Calibration – ULS

- **Static Analyses Driven Piles**
- **Dynamic Analyses Driven Piles**
- **Case History**

3 LRFD DESIGN
Example of Code Calibration – ULS

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).



NCHRP 507 Recommended Resistance Factors Driven Piles – Static Analyses

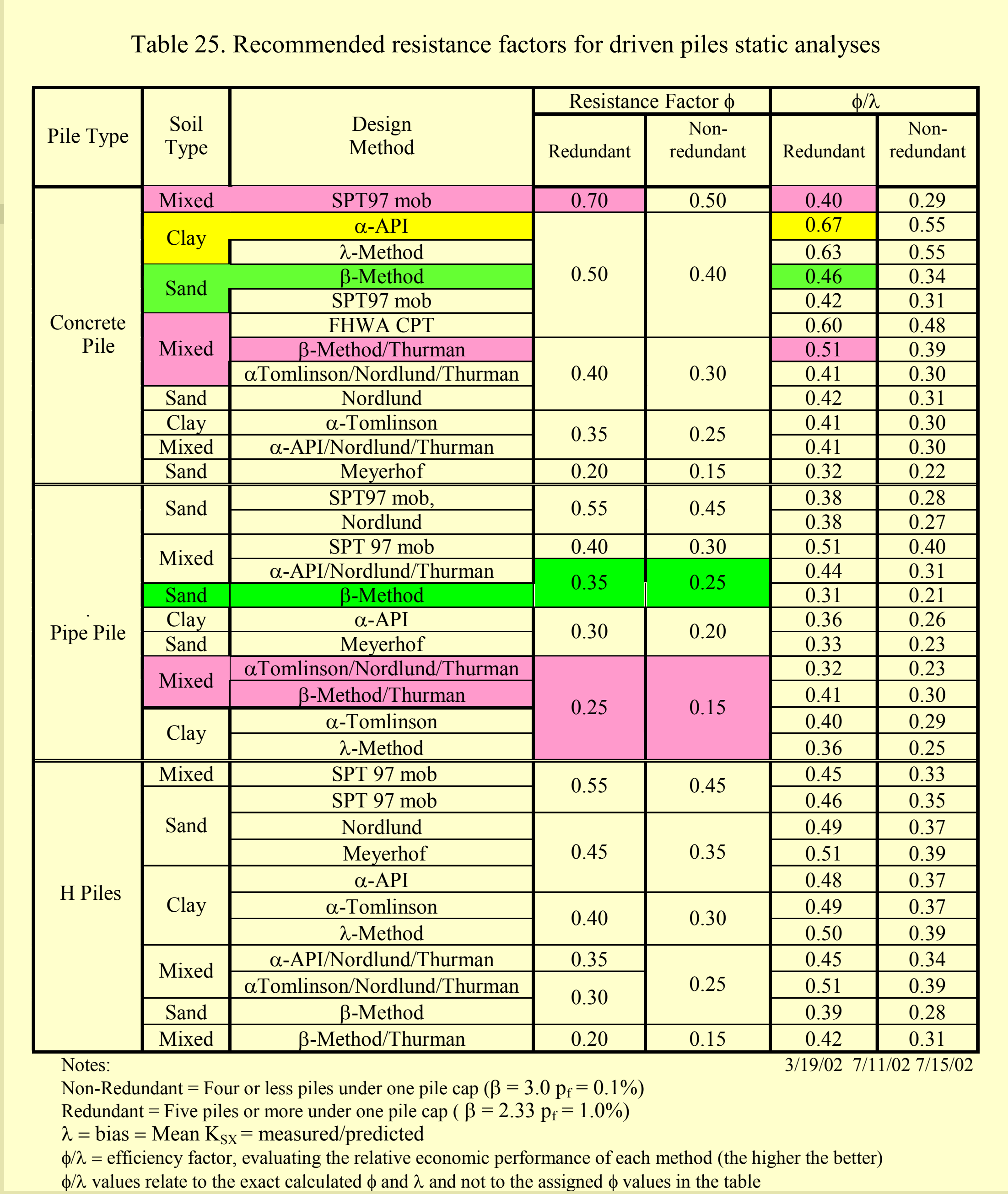


Table 25. Recommended resistance factors for driven piles static analyses

Pile Type	Soil Type	Design Method	Resistance Factor ϕ		ϕ/λ	
			Redundant	Non-redundant	Redundant	Non-redundant
Concrete Pile	Mixed	SPT97 mob	0.70	0.50	0.40	0.29
	Clay	α-API	0.50	0.40	0.67	0.55
		λ-Method			0.63	0.55
	Sand	β-Method			0.46	0.34
		SPT97 mob			0.42	0.31
	Mixed	FHWA CPT			0.60	0.48
		β-Method/Thurman	0.40	0.30	0.51	0.39
		αTomlinson/Nordlund/Thurman			0.41	0.30
	Sand	Nordlund			0.42	0.31
	Clay	α-Tomlinson	0.35	0.25	0.41	0.30
	Mixed	α-API/Nordlund/Thurman			0.41	0.30
	Sand	Meyerhof	0.20	0.15	0.32	0.22
Pipe Pile	Sand	SPT97 mob,	0.55	0.45	0.38	0.28
		Nordlund			0.38	0.27
	Mixed	SPT 97 mob	0.40	0.30	0.51	0.40
		α-API/Nordlund/Thurman	0.35	0.25	0.44	0.31
	Sand	β-Method			0.31	0.21
	Clay	α-API	0.30	0.20	0.36	0.26
	Sand	Meyerhof			0.33	0.23
	Mixed	αTomlinson/Nordlund/Thurman	0.25	0.15	0.32	0.23
		β-Method/Thurman			0.41	0.30
	Clay	α-Tomlinson			0.40	0.29
		λ-Method			0.36	0.25
H Piles	Mixed	SPT 97 mob	0.55	0.45	0.45	0.33
	Sand	SPT 97 mob			0.46	0.35
		Nordlund	0.45	0.35	0.49	0.37
		Meyerhof			0.51	0.39
	Clay	α-API			0.48	0.37
		α-Tomlinson	0.40	0.30	0.49	0.37
		λ-Method			0.50	0.39
	Mixed	α-API/Nordlund/Thurman	0.35	0.25	0.45	0.34
		αTomlinson/Nordlund/Thurman	0.30		0.51	0.39
	Sand	β-Method			0.39	0.28
	Mixed	β-Method/Thurman	0.20	0.15	0.42	0.31

Notes: 3/19/02 7/11/02 7/15/02

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 ($\beta = 2.33$ $p_f = 1.0\%$)

λ = bias = Mean K_{SX} = 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 LRFD DESIGN
Example of Code Calibration – ULS

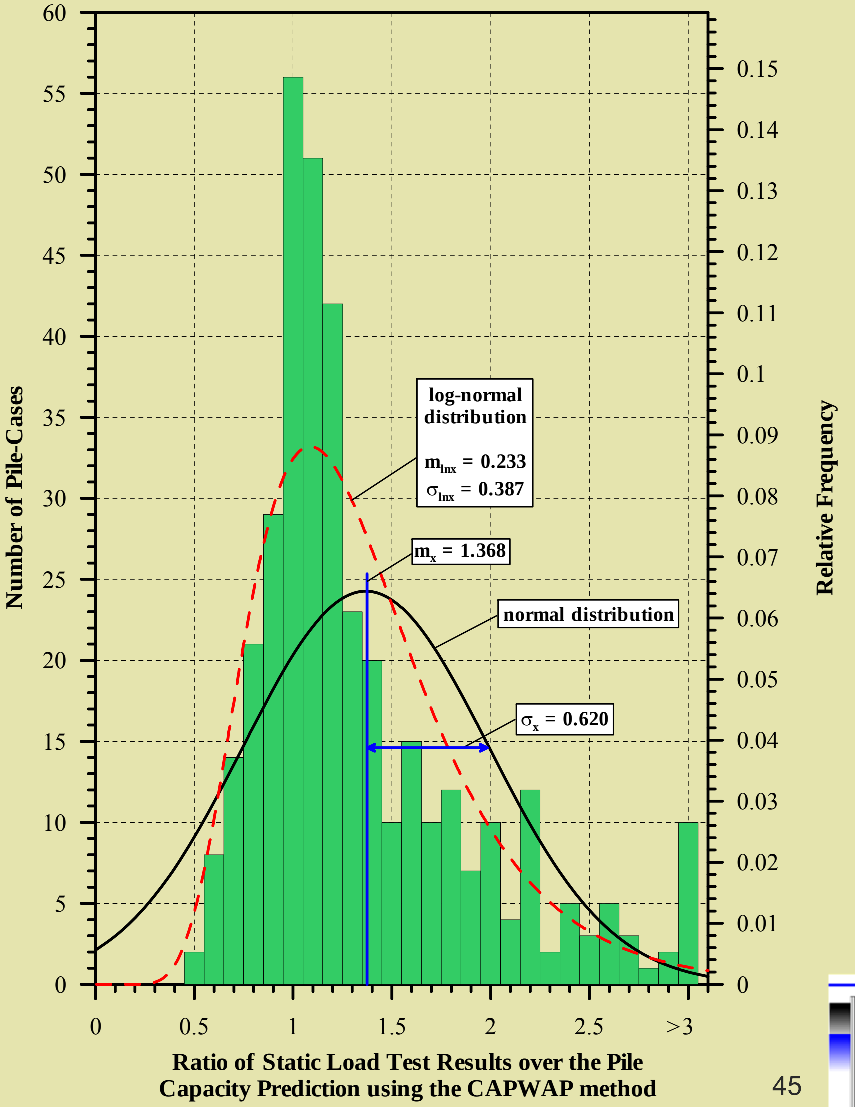
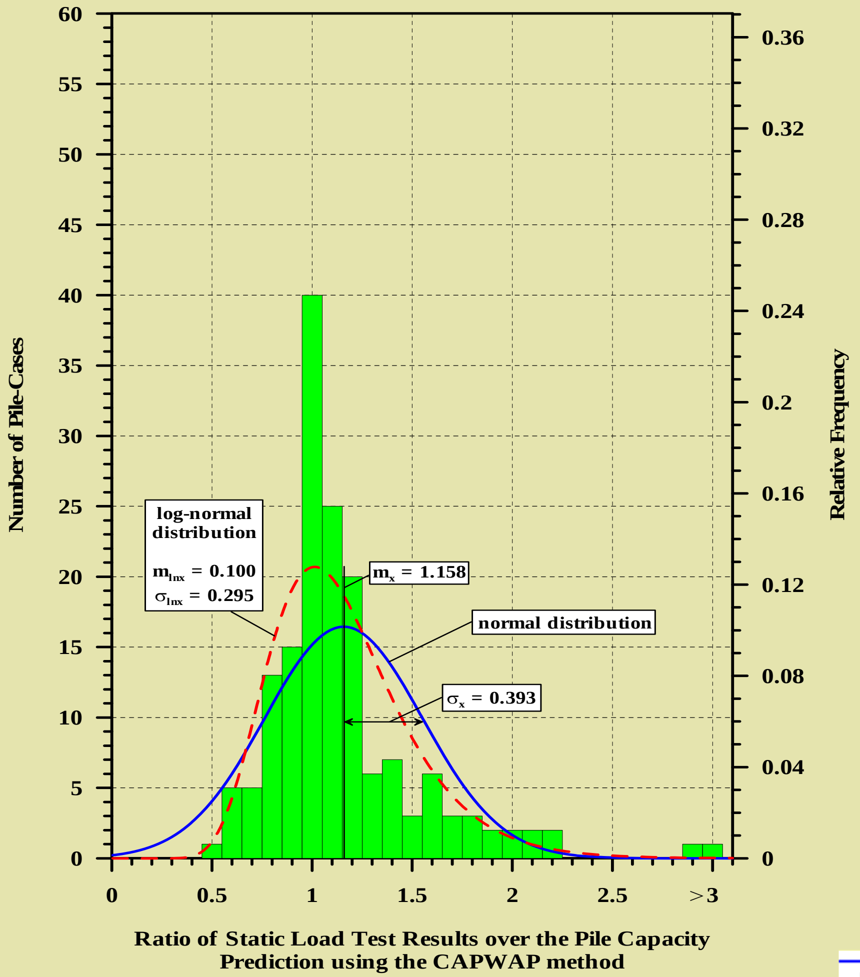


Figure 6. Histogram and Frequency Distributions for all (377 cases) Measured over Dynamically (CAPWAP) Calculated Pile-Capacities in PD/LT2000 (Paikowsky et al., 2004).

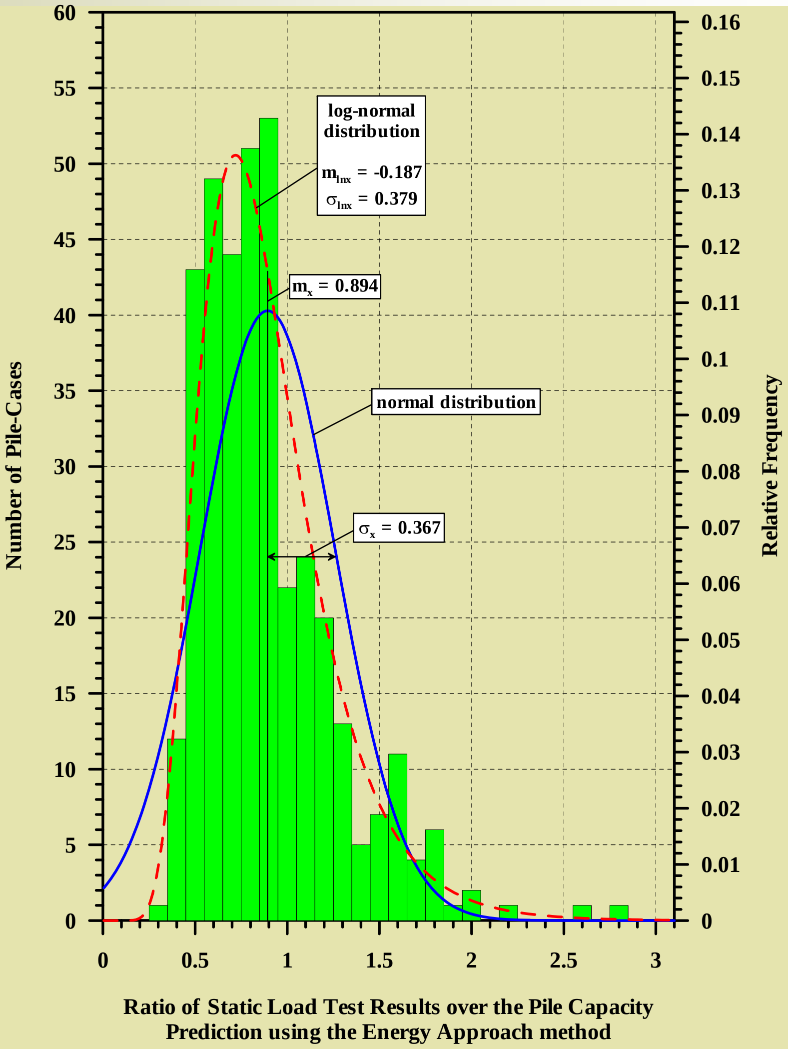
3 LRFD DESIGN
Example of Code Calibration – ULS

Histogram & Frequency Distributions for all BOR (162) CAPWAP pile-cases in PD/LT2000



3 LRFD DESIGN
Example of Code Calibration – ULS

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



3 LRFD DESIGN
Recommended resistance factors
Driven Piles – Dynamic Analyses

Table 27. Recommended resistance factors for driven piles dynamic analyses

Method		Case	Resistance factor, ϕ		ϕ/λ	
			Redundant	Non-Redundant	Redundant	Non-Redundant
Dynamic Measurements	Signal Matching (CAPWAP)	EOD	0.65	0.45	0.40	0.28
		EOD, AR<350, Bl. Ct.<16BP10cm	0.40	0.25	0.16	0.09
		BOR	0.65	0.50	0.56	0.44
	Energy Approach	EOD	0.55	0.40	0.49	0.37
		BOR	0.40	0.30	0.52	0.41
Dynamic Equations	ENR	General	0.25	0.15	0.16	0.09
	Gates	General	0.75	0.55	0.41	0.30
	FHWA modified	General	0.40	0.25	0.38	0.28
WEAP		EOD	0.40	0.25	0.24	0.15

Notes: β = 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.($\beta = 2.33$ $p_f = 1.0\%$) λ = bias = Mean K_{SX} = 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 LRFD DESIGN

Recommended resistance factors

Static Load Test

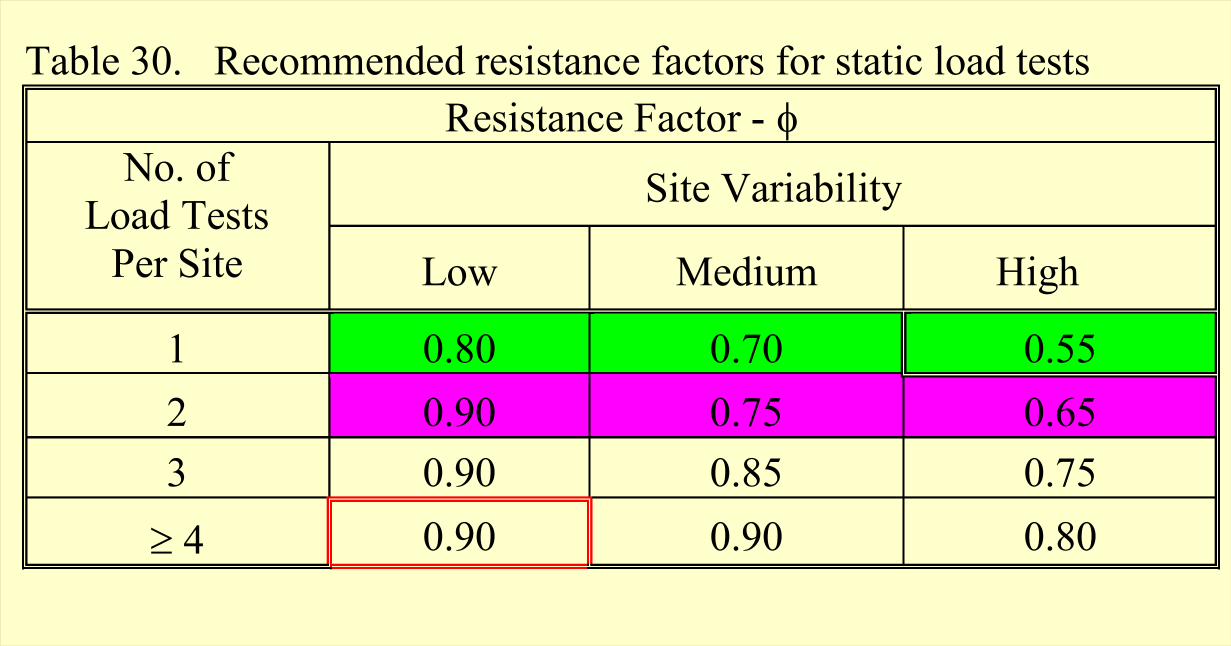


Table 30. Recommended resistance factors for static load tests

Resistance Factor - ϕ			
No. of Load Tests Per Site	Site Variability		
	Low	Medium	High
1	0.80	0.70	0.55
2	0.90	0.75	0.65
3	0.90	0.85	0.75
≥ 4	0.90	0.90	0.80

3 LRFD DESIGN

Recommended Number of Pile Tests During Production

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

Site Var.		Low		Medium		High	
No. of Piles	Method	EA	CAPWAP	EA	CAPWAP	EA	CAPWAP
	Time	EOD	BOR	EOD	BOR	EOD	BOR
≤ 15		4	3	5	4	6	6
16 - 25		5	3	6	5	9	8
26 - 50		6	4	8	6	10	9
51 – 100		7	4	9	7	12	10
101-500		7	4	11	7	14	12
> 500		7	4	12	7	15	12

EA = Energy Approach Analysis

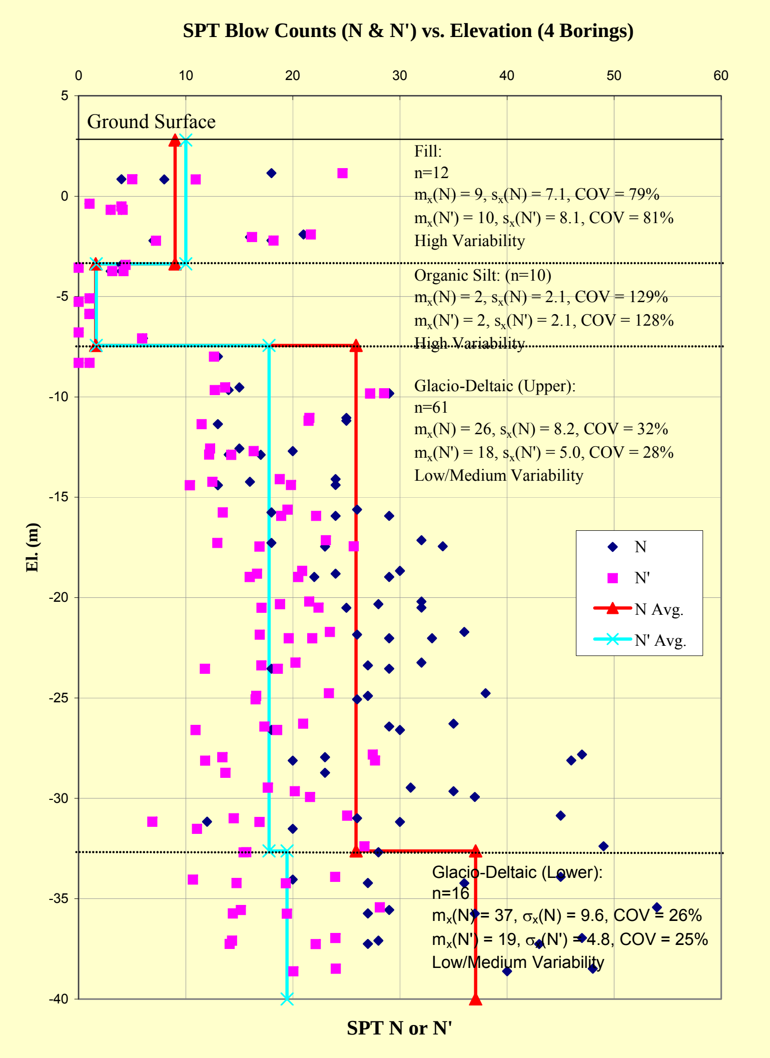
CAPWAP = Signal Matching Analysis

EOD = End of Driving

BOR = Beginning of Restrike

Minimum one test under each substructure

Site Variability Assessment - Example



Area A (4 borings)				
Layer No.	n	m_x	σ_x	COV
1	12	10	8.1	81%
2	10	2	2.1	128%
3	61	18	5.0	28%
4	16	19	4.8	25%
n – Number of Values				

Variability

High

High

Low-Med

Low

Area A Using SPT – 4 Borings

7 SUMMARY OF LECTURE 6

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.

7 SUMMARY OF LECTURE 6

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.

7 SUMMARY OF LECTURE 6

7. 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

7 SUMMARY OF LECTURE 6

8. The examination of either factors of safety or resistance factors on the basis of their absolute values is misleading and efficiency factors (ϕ/λ or FSx λ) 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.