LRFD Application in Driven Piles (Recent Development in Pavement & Geotech at LTRC)

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Outline

- Problem statement
- Different design methods
- Statistical concept
- Methods used in LADOTD for driven piles
- LRFD calibration
- Conclusion
Problem Statement and Research Objectives

- Working Stress Design (WSD), Allowable Stress Design (ASD) vs. LRFD
- Bridge super structures vs. Foundation
- Federal Highway Administration and ASSHTO set a transition date of October 1, 2007
- Resistance Factor ($\Phi$) reflecting Louisiana soil and DOTD design process
Calibration of the Design Code for Bridge Substructure

- Identify the load and resistance parameters for bridge substructure
- Formulate the limit state functions
- Develop the reliability analysis procedure and calculate reliability indices
- Select the target reliability index
- Determine the load and resistance factors for bridge substructure (including earth pressure related loads)
Stress Design Methodologies vs. LRFD

- Working Stress Design (WSD) – also called Allowable Stress Design (ASD)

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

where, \( Q = \) design load; \( Q_{\text{all}} = \) allowable design load; \( R_n = \) resistance of the structure, and \( Q_{\text{ult}} = \) ultimate resistance of the structure
Stress Design Methodologies vs. LRFD

- Limit State Design (LSD)
  - Ultimate Limit Stress (ULS)
    - Factored resistance ≥ Factored load effects
  - Service Limit Stress (SLS)
    - Deformation ≥ Tolerable deformation to remain serviceable
Load and Resistance Factor Design (LRFD)

\[ \phi R_n \geq r_D Q_D + r_L Q_L = \sum r_i Q_i \]

where, \( \Phi \) = resistance factor, \( R_n \) = ultimate resistance; \( r_D \) = load factor for dead load; \( r_L \) = load factor for live load; \( r_i \) = corresponding load factor, and \( Q_i \) = summation of load
Working Stress Design (WSD) vs. LRFD

- **Working Stress Design (WSD)**
  - Load vs. Displacement
  - $S_D$ vs. $Ru$
  - Factor of Safety (FS)

- **Load & Resistance Factor Design (LRFD)**
  - Load vs. Displacement
  - $S_D$ vs. $Ru$
  - $\phi Ru$
  - $\gamma S_D$

- **Limit States Design (LSD)**
  - Load vs. Displacement
  - $S_D$ vs. $Ru$
Random Variation

- Load and resistance parameters are random variables
- Reliability index is a measure of structural performance
- Practical procedure for calculation of the reliability indices
- Target reliability index
- Load and resistance factors that result in design that is close to the target reliability index
Statistical Concept

- Mean (μ) and Mode
- Variance (σ^2) and Standard Deviation (σ)

\[ \sigma^2 = \frac{\sum (x_i - \bar{x})^2}{n-1} \]

- Coefficient of Variation (COV)

\[ COV = \frac{\sigma}{\mu} \]

- Probability Density Function (PDF)
Limit State Function can be defined as
\[ g = R - Q \]
Reliability Index, $\beta$

\[ f_U = \text{probability density of } U \]

\[ \beta = \frac{g}{\sigma_g} = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \]

$\beta$ : reliability (or safety) index

$P_f = \text{shaded area}$

$\ln R - \ln S = \bar{U}$
Reliability Based FS

Load effect = Q

Capacity = R

design load

design capacity
### Relationship between $\beta$ and $P_f$

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<tr>
<th>$P_f$</th>
<th>$\beta$</th>
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<tr>
<td>10-1</td>
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First Order Second Moment (FOSM)

Load and Resistance Factor Design (LRFD)

\[ \phi R_n \geq r_D Q_D + r_L Q_L = \sum r_i Q_i \]

where, \( \Phi \) = resistance factor, \( R_n \) = ultimate resistance; \( r_D \) = load factor for dead load; \( r_L \) = load factor for live load; \( r_i \) = corresponding load factor, and \( Q_i \) = summation of load
First Order Second Moment (FOSM)

\[ \phi R_n \geq r_D Q_D + r_L Q_L = \sum r_i Q_i \]  

(1)

\[ \beta = \frac{\ln \left( \frac{\lambda_R R_n}{Q_D} + \lambda_Q \right) \sqrt{1 + COV_{QD}^2 + COV_{QL}^2}}{\sqrt{\ln (1 + COV_{R}^2)(1 + COV_{QD}^2 + COV_{QL}^2)}} \]  

(2)

Combining eq (1) and (2) using \( R_n \)

\[ \phi = \frac{\frac{\gamma_D Q_D}{Q_L} + \gamma_L}{\left( \frac{\lambda_Q Q_D}{Q_L} + \lambda_Q \right) \exp \left( \beta \ln \left( 1 + COV_{R}^2 \right) \right)} \times \sqrt{\left( 1 + COV_{QD}^2 + COV_{QL}^2 \right)} \]  

AASHTO (1994)

\[ \lambda_{QD} = 1.08, \quad \lambda_{QL} = 1.15, \quad r_D = 1.25, \quad r_L = 1.75, \quad COV_{QD} = 0.13, \quad COV_{QL} = 0.18 \]

\( \gamma_D, \gamma_L = \) dead and live load factors

\( Q_D/Q_L = \) dead to live load ratio

\( \lambda_{QD}, \lambda_{QL} = \) dead and live load bias factors
Methods used in LADOTD
(Ultimate Capacity for Driven Piles)

- Static method
  - $\alpha$ method - General adhesion for cohesive soil (Tomlison 1979)
  - Nordlund method

- CPT method
  - Schmertmann, LCPC, de Ruiter and Beringen

- Dynamic Analysis
  - GRL WEAP

- Dynamic Measurement
  - CAPWAP

- Measured Ultimate Pile Capacity
  - Davisson, Butler-Hoy
Davisson (Interpretation of Pile Load Tests)

\[ \Delta = \frac{Q}{AE} \]

\[ x = 0.15 + \frac{D}{120} \text{ (in)} \]
**Butler-Hoy (Interpretation of Pile Load Tests)**

Static Load Test Results

Load (Tons)

Settlement (in)

- **Slope** = 0.05 in./ton

$Q_{ult}$
Cone Penetration Test (CPT) Method

- Penetration Rate: 2 cm/sec
- Sleeve friction, $f_s$
- Tip resistance, $q_c$

Cone rod: 36 mm dia.
Ultimate Pile Capacity from CPT

\[ Q_{ult} = Q_{tip} + Q_{shaft} \]

Shaft friction Capacity,
\[ Q_{shaft} = \sum f_i \cdot A_i \]

End-bearing Capacity, \( Q_{tip} \)
\[ = q_t \cdot A_t \]
Schmertmann method (CPT)

where,

\( q_t = \frac{q_{c1} + q_{c2}}{2} \)

\( f = \alpha_c f_s \)

- \( q_t \): unit bearing capacity of pile
- \( f \): unit skin friction
- \( \alpha_c \): reduction factor (0.2 ~ 1.25 for clayey soil)
- \( f_s \): sleeve friction

\[ Q_s = \alpha_s \left( \sum_{y=0}^{8D} \frac{y}{8D} f_s A_s + \sum_{y=8D}^{L} f_s A_s \right) \]

\[ Q_{ul} = Q_t + Q_s = q_t A_t + f A_s \]
LCPC method (CPT)

\[
q_t = k_b \ q_{eq} \ (\text{tip})
\]

\[
k_b = 0.6 \ \text{clay-silt}
\]

\[
0.375 \ \text{sand-gravel}
\]

\[
f = \frac{q_{eq} \ (\text{side})}{k_s} < f_{\text{max}}
\]

\[
k_s = 30 \ \text{to} \ 150
\]
de Ruiter and Beringen (CPT)

- In clay
  \[ S_u(\text{tip}) = \frac{q_c(\text{tip})}{N_k} \]
  \[ q_t = N_c.S_u(\text{tip}) \]
  \[ f = \beta.S_u(\text{side}) \]
  \[ N_k = 15 \text{ to } 20 \]
  \[ N_c = 9 \]
  \[ \beta = 1 \text{ for NC clay} \]
  \[ = 0.5 \text{ for OC clay} \]

- In sand
  \[ q_t \text{ similar to Schmertmann method} \]
  \[ f = \min \left\{ \begin{array}{l}
  f_s \text{ (sleeve friction)} \\
  q_c(\text{side}) / 300 \text{ (compression)} \\
  q_c(\text{side}) / 400 \text{ (tension)} \\
  1.2 \text{ TSF}
  \end{array} \right\} \]
Implementation into a Computer Program

- Louisiana Pile Design by Cone Penetration Test
- [Link](http://www.ltrc.lsu.edu/)
Histograms

- De Ruiter & Beringen method
- LCPC method
- Schmertmann method
- $\alpha$ method
Resistance Factors, $\phi$ (Davisson)

- LCPC method
- Schmertmann method
- Static method

Ratio of dead load to live load ($Q_D/Q_L$)

Resistance factor, $\phi$
Resistance Factors, $\phi$ (Butler-Hoy)

![Graph showing resistance factors for various methods.](Image)
# Resistance Factors, $\phi$ ($\beta_T=2.5$)

<table>
<thead>
<tr>
<th>Load Test Interpretation Method</th>
<th>Pile Capacity Prediction Method</th>
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<td>De Ruiter</td>
<td>0.68</td>
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</tbody>
</table>
Conclusions

- **Tentative** resistance factors ($\phi$) for Louisiana soil were evaluated for different driven pile design methods (Research is on going).
- Values of resistance factor depend on the pile load test interpretation and design methods.
- LRFD in deep foundation can improve its reliability due to more balanced design.
- There is a strong need for more statistical data to get more rational resistance factor.
LRFD Implementation in Louisiana

- Dr. Ching Tsai
- Wednesday 10:00 - 11:45 a.m.
- Session 83: Geotechnical Services
- Meeting Room 3
Acknowledgement

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- LTRC Project No. 07-2GT.
References

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- Bea, Robert G. 2006 presentation
- Nowak, Andrzej S. 2007 TRB presentation.
- Mayne, Paul W.  
  <http://www.ce.gatech.edu/~geosys/Faculty/Mayne>
- NCHRP report 507: Load and Resistance Factor Design (LRFD) for Deep Foundation.
THANK YOU!

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