RESISTANCE FACTOR CALIBRATION FOR DRIVEN PILES

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PAVEMENT AND GEOTECHNICAL SERVICES
Resistance factors are the inverse of safety factors that accounts for the variability of each individual contributing factor of resistance.
WHY ARE WE DOING IT?

FHWA has tied federal bridge funding to the adoption of LRFD specifications. All structures starting preliminary design by October 1, 2007 will use the LRFD Bridge Design Specifications.
Stability Minimum Factor of Safety = 1.3

Experience Based Approach: *try, try again*
WHAT’S WRONG WITH USING FS?

• Use conservative parameters
  – Consistency
  – Conflict in conservatism
  – Economic issues
  – Problem w/behavior prediction
• FS gives false sense of safety
• A lack of risk assessment
Pile Resistance Predictions

Ratio of Predicted to Observed Capacity

Number of Predictions

Pipe Pile
24 Values

Underpredictions
Overpredictions
Median
Mean
## Variation of Soil Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C.V.</th>
<th>Parameter</th>
<th>C.V.</th>
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<tr>
<td>Porosity</td>
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<td>Coeff. of Compressibility</td>
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<td>Specific Gravity</td>
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<td>Preconsolidation Pressure</td>
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<td>Water Content</td>
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<tr>
<td>Silty Clay</td>
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<td>Sandy Clay</td>
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<tr>
<td>Clay</td>
<td>0.13</td>
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<td>Degree of Saturation</td>
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<td>SPT</td>
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<td>Unit Weight</td>
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<td>CPT</td>
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<td>Permeability</td>
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<td>Friction Angle</td>
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<tr>
<td>Dry of Optimum</td>
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<td>Gravel</td>
<td>0.07</td>
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<tr>
<td>Wet of Optimum</td>
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<td>Sand</td>
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<td>Cohesion</td>
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<tr>
<td>Structure Element</td>
<td>Median Bias $B_{50Ru}$</td>
<td>Capacity Uncertainty COV %</td>
<td>Structure Element</td>
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<td>Tubular Braces</td>
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<td>Plates</td>
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<td>10 - 12</td>
<td>Stiffened Panels</td>
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<td>15 - 18</td>
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<td>10 - 12</td>
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<tr>
<td>hydrostatic</td>
<td>1.4</td>
<td>10 - 12</td>
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<td>15 - 16</td>
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<tr>
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<td>(machined connections)</td>
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<tr>
<td>sands</td>
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<td>50 - 60</td>
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<tr>
<td>clays</td>
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<td>25 - 35</td>
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<tr>
<td>sands</td>
<td>1.1</td>
<td>40 - 50</td>
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FACTOR OF SAFETY

- Does not reflect the field investigation and lab testing efforts
- Does not account for the analytical techniques used
- Rewards field monitoring (PDA, CAPWAP, load test) without proper evaluation of the variation of the test results
- Same FS different performance and risk
WHY LRFD?

- **ASD**
  - Safety factors (subjective)
  - Stress is not a good measurement of resistance
  - Inadequate account of variability

- **LFD**
  - Load factor applied to each load combination
  - No risk assessment

- **LRFD**
  - Accounts for variability
  - Uniform level of safety
  - Risk Assessment

\[
\sum DL + \sum LL \leq R_u / FS
\]

\[
\gamma \left( \sum \beta_{DL} DL + \sum \beta_{LL} LL \right) \leq \phi R_u
\]

\[
\eta \left( \sum \gamma_{DL} DL + \sum \gamma_{LL} LL \right) \leq \phi R_u
\]
ASD, LFD, LRFD
Reliability Index

- Definition

\[ \text{RI}(\beta) = \frac{E(FS) - 1}{\sigma(FS)} \]

\[ \beta = \ln \left( \frac{E(R) \cdot \sqrt{1 + V_R^2}}{E(Q) \cdot \sqrt{1 + V_Q^2}} \right) \]

- Defines probability of failure
Reliability vs. Probability of Failure

- Normal
- Unknown
Reliability Index = $\beta$

- $P_f = 1 - \Phi[\beta]$
- $P_f \approx 0.475 \exp(-\beta^{1.6})$
- $P_f \approx 10^{-\beta}$
- $P_s = 1 - P_f = \text{Reliability}$
WHAT DO WE NEED TO DETERMINE RELIABILITY INDEX?

• A deterministic model (slope stability, $\alpha$-method)
• A performance function (FS from STABL, capacity from Driven)
• The expected value (weighted average) and standard deviation of the parameters ($C, \phi$)
• A definition of the limit state (FS=1)
• A method to estimated the expected value and standard deviation of the limit state
STEPS TO DETERMINE RESISTANCE FACTORS

1. Determine acceptable probability of failure (reliability index)
2. Estimate variability of soil parameters
3. Determine systematic errors or bias
4. Calculate resistance factor(s) $\phi$
METHODS OF RESISTANCE FACTOR CALIBRATION

• Calibration by fitting ASD
• Calibration using reliability theories
  – FOSM
  – AFOSM
  – FORM (NCHRP 507)
  – SORM
  – Monte Carlo
EVOLUTION OF RESISTANCE FACTORS FOR DRIVEN PILES

- **1992 AUSTROAD**
  - 0.8 to 0.9 (load test)
- **1992 Ontario**
  - 0.4(c), 0.3(t), 0.6(sc), 0.4(st)
- **1995 Australian Standard**
  - 0.7 to 0.9 (load test)
  - 0.45-0.65 (static pile analyses)
  - 0.5 to 0.85 (dynamic monitoring)
- **1997 Eurocode**
  - 0.67 to 0.91
- **1999 Goble**
  - 0.63 to 0.77
- **1998 & 2004 AASHTO**
  - 0.7 (α-method)
  - 0.5 (β-method)
  - 0.8 (load test)
- **2004 NCHRP**
  - 0.24 to 0.6 (clay)
  - 0.13 to 0.58 (sand)
  - 0.26 to 0.84 (mixed)
  - 0.23 to 0.75 (dynamic)
- **2006 AASHTO**
  - 0.35 (α-method)
  - 0.25 (β-method)
  - 0.45 (Nordlund)
  - 0.55 to 0.8 (load test)
PRACTICE BEFORE CALIBRATION

• Fitting ASD

\[ \phi = \frac{\gamma_{DL} \cdot \frac{DL}{LL} + \gamma_{LL}}{(DL/LL + 1) \cdot FS} \]

\( DL/LL = 3.0, \) then \( \phi = 1.375/FS \)

\( DL/LL = 1.0, \) then \( \phi = 1.5/FS \)

\( 1.25/FS < \phi < 1.75/FS \)

• Finagled Resistance Factors
  – no risk analysis
DOTD’S CALIBRATION EFFORT

- PI – Dr. Murad Abu-Farsakh
  - Dr. Sungmin Yoon (Research Associate)

- Driven piles
  - Schedule
    - Summer 2007
  - Methods to be Calibrated
    - Tomlinson (α-method)
    - Nordlund/Thurman Method
    - CPT

- Drilled Shafts
  - Starting after summer 2007
PROCEDURES

• Data collection
• Digitize data
• Interpret data
• Re-evaluate capacities using the methods to be calibrated
• Statistic analysis
PROBLEMS ENCOUNTERED

- Data interpretation (judgment)
- Quality of soil boring logs
- Quality of load test data
- Difficult to differentiate among different methods ($\alpha$, $\beta$, Norlund) due to mixed soil conditions
- Difficult to separate end bearing from total capacity based on the traditional load tests
- Insufficient database for $\beta$ and Norlund methods
- A lack of good quality tests from north Louisiana
PRELIMINARY RESISTANCE FACTORS FOR DRIVEN PILES

- $\lambda = 1.18$ means 15% underprediction (avg)
  - National average 1.20 (2004 NCHRP 507)

- $\beta = 2.33$
  - $\phi = 0.65$ for DD/LL of 1  $FS_{\text{avg}} = 2.3$ (calculated)
  - $\phi = 0.61$ for DD/LL of 3  $FS_{\text{avg}} = 2.6$ (true)

- $\beta = 3.0$
  - $\phi = 0.51$ for DD/LL of 1  $FS_{\text{avg}} = 2.9$ (calculated)
  - $\phi = 0.48$ for DD/LL of 3  $FS_{\text{avg}} = 3.3$ (true)
IMPLEMENTATION CONCERNS

- Service state – no risk assessment
- Slope stability – difficult to calibrate
- Small database used for calibration
- Model representation – limit to Tomlinson’s $\alpha$ method
- System reliability vs. component reliability
  – Retaining wall, embankment, pile group
- Difficult to quantify experience
- Requires the knowledge of database
CHALLENGES (1)

• Very short transition from ASD to LRFD
• Database update
• On-going resistance factors update
• Pure clay load tests vs. pure sand load tests
• Skin friction vs. end bearing
• Geology
• Comfort level of the resistance factors
CHALLENGES (2)

- Concept of redundancy and ductility
- Educate the geotechnical community
- Experience from local geotechnical practices is lost
- New methods require new calibration effort
OTHER FACTORS AFFECTING RESISTANCE FACTORS

- Site variability
  - Low: \( \text{cov} < 0.25 \)
  - Medium: \( 0.25 < \text{cov} < 0.40 \)
  - High: \( \text{cov} > 0.4 \)

- Redundancy

- Ductility
APPLICATION OF LRFD
LIMIT STATES

- **Strength Limit (5)**
  - Failure
- **Service Limit (4)**
  - Movement
- **Extreme Limit (2)**
  - Improbable loads
- **Fatigue Limit**
  - Cycles of loads
STRENGTH LIMIT STATES

- **Strength I**
  - Normal vehicular with basic load combination
  - No wind

- **Strength II**
  - Permit design vehicles
  - No wind

- **Strength III**
  - Wind load combination (55 mph)
  - No live load
STRENGTH LIMIT STATES

• Strength IV
  – High dead to live load ratio (>7.0)
  – Controls for “long span bridges”
  – No live load

• Strength V
  – Normal vehicular use
  – Wind velocity of 55 mph
EXTREME LIMIT STATES

- Extreme Event I
  - Earthquake loading combination
- Extreme Event II
  - Ice loading combination
  - Vehicle/vessel collision load combination
  - Certain hydraulic events
SERVICE LIMIT STATES

- Service I
  - Normal operation
  - 55 mph wind

- Service II & III
  - Structure related

- Service IV
  - Tension in pre-stressed concrete substructures
  - Crack control
GEOTECHNICAL DESIGN PROCESS

• ASD
  – Field investigation determined based on a predetermined FS
  – Allowable loads vs. depths
    • Pile order lengths or plan lengths determined
  – Check serviceability requirements

• LRFD
  – Field investigation determined based on an appropriate $\phi$
  – Choose resistance factors based on load tests and site variability
  – Conduct field and lab tests
  – Refine field and lab tests
  – Check service states using $\phi = 1$
  – Feedback during construction
LOAD TEST

- **ASD**
  - Test to failure or 3 times design load

- **LRFD**
  - Test to nominal resistance or 150% of nominal resistance
CONTINUING EFFORTS (1)

- Collect more load test data
- Group database based on geology
- Attempt to calibrate resistance factors for pile installed in the Pleistocene or stiff soils
- Separate tip resistance from skin friction using dynamically monitored piles
CONTINUING EFFORTS (2)

• Continuous update of resistance factors
  – Will need consultants’ help in getting new load tests
  – Include more published methods, if sufficient good quality database exists

• Update DOTD’s Bridge Design Manual

• Internal and external education on LRFD subjects

• Publish the research results