The Not So Hidden Cost in Deep Foundation Design

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Deep Foundations

- H-pile
- Cast-in-Place Pipe
- Precast Concrete
- Timber
Deep Foundation Choice?

- Type of Load (axial, lateral, torsion)
- Magnitude of Load
- Project Size & Complexity
- Site Conditions
- Environmental Conditions
- Local Availability & COST
- Familiarity (engineer, client) & complacency
- **Foundation Cost Controlled by Design Uncertainty** (conservatism & safety factor)
Deep Foundation Design Uncertainty

- **Site Variability**
  - Axial, lateral, depth to bearing stratum
  - Strength, stiffness, test quality
  - Typically test < 0.01% of site

- **Design Method:** \( R_N = R_{\text{side}} + R_{\text{base}} \)
  - Calibration, empiricism, codes, resistance or safety factors based on uncertainty

- **Construction Quality**
  - Contractor experience
  - Quality of supervision
Deep Foundation Uncertainty

- **Site Variability**
- 50 ft x 50 ft Footing
- SPT Sampler
- 18 in x 2 in dia
- Sampling every 2.5 ft (60% of soil column)
- Assume each boring represents 8 in dia soil column
- Five borings sample ~0.01% of 1 million cf
- Concrete testing typically samples about 0.2%
Deep Foundation Uncertainty

- **LRFD = Load & Resistance Factor Design**
- **Probabilistic Limit State Design**

\[ \sum (\gamma_i Q_i) \leq \sum (\varphi_i R_{Ni}) \]

- \(\gamma_i\) = Load Factors (>1) (service, strength, extreme)
- \(Q_i\) = Nominal Loads (live, dead, wind, earthquake)
- \(\varphi_i\) = Resistance Factor (<1), depends on \(R_{Ni}\) (reduced by 0.10 for non-redundant foundations)
- \(R_{Ni}\) = Nominal Resistance (theoretical or msd.)
- **Target Probability of Failure = 1 in 1000**
## Deep Foundation Uncertainty

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Method for $R_N$</th>
<th>AASHTO LRFD $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven</td>
<td>Side &amp; Base, Clay</td>
<td>0.25 - 0.40</td>
</tr>
<tr>
<td>Driven</td>
<td>Side &amp; Base, Sand</td>
<td>0.40</td>
</tr>
<tr>
<td>Driven</td>
<td>ENR / Gates Formula</td>
<td>0.10 / 0.40</td>
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<tr>
<td>Driven</td>
<td>Wave Equation</td>
<td>0.40</td>
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<tr>
<td>Drilled Shaft</td>
<td>Side, Clay ($\alpha$)</td>
<td>0.55</td>
</tr>
<tr>
<td>Drilled Shaft</td>
<td>Side, Sand ($\beta$)</td>
<td>0.45</td>
</tr>
<tr>
<td>Drilled Shaft</td>
<td>Base, Bearing Eqn.</td>
<td>0.40</td>
</tr>
<tr>
<td>Driven</td>
<td>Dynamic Test (5%+)</td>
<td>0.65</td>
</tr>
<tr>
<td>Drilled Shaft</td>
<td>Dynamic Test (5%+)</td>
<td>0.60</td>
</tr>
<tr>
<td>Driven / Shaft</td>
<td>Static Test, med. COV</td>
<td>0.70 (0.50 - 0.90)</td>
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</tbody>
</table>
Reduce Cost by Reducing Uncertainty:

- Informed design (integrated investigation: geophysics + insitu testing + sampling)
- Design verification (testing)
- Optimization (redesign)
  - reduce length, size, number
  - change type (driven, drilled, anchor)
  - reduce cost and construction time ($$)
  - FLT’s experience - savings 5X test cost
- Quality control testing to assure performance & reduce remediation cost
Integrated Ground Investigation

- Measure (not guess) ground properties for foundation design
- More time characterizing site → more reliable design
- Staged approach - progressively more targeted techniques
- Geophysical techniques provide overview of geological conditions
- Intrusive investigation calibrates geophysical information
- Insitu testing (CPT/DMT) reduces uncertainties associated with sampling disturbance and laboratory testing
- Insitu profiling (CPT) identifies thin layers missed by drilling and sampling program
- SPT not so great (“standard”, drilling disturbance, energy)
- Sampling and testing to characterize specific problem zones
- Does not have to cost more, and can cost less
- Full scale tests to calibrate design methods for a site?
- Preliminary pile tests included to prepare better plans?
Electroresistivity

Potential BH Target

Line 17a

Model resistivity with topography
Iteration 4 RMS error = 8.3

Roof may be less than 5 m thick if air void is present at top of feature.

Line 17b

West

East

Resistivity in ohm.m

Horizontal scale is 13.28 pixels per unit spacing
Vertical exaggeration in model section display = 1.09
First electrode is located at 0.0 m.
Last electrode is located at 213.0 m.

Unit Electrode Spacing = 3.0 m.

www.fugro.com
Electromagnetic Conductivity

Electromagnetic Conductivity Profile

SOLUTION FEATURE

CPT 1

CPT 2

SUBSURFACE OBSTRUCTION

Apparent...
Seismic Refraction Tomography

Bedrock Mapping

- Sand
- Overburden
- Weathered Bedrock
- More Competent Bedrock
Insitu Cone Penetrometer Test (CPT)

- Robust push-in tool (ASTM D5778)
- Profiles penetration resistance
- Estimates soil type
- Undrained shear strength (clay)
- Friction angle (granular soils)
- Footing settlement, bearing pressure, pile capacity
- Compaction quality control
- Depth to cavities or bearing stratum
- Optimize borehole program
Shear Strength
\[ S_u = \frac{q_c}{N_k} \]
\[ 15 < N_k < 20 \]
CPT Pore Pressure Dissipation Tests

Coefficient of Horizontal Consolidation – $c_h$

Design of Wick Drains, Embankment Settlement Rates

Robertson 1992

(x 1.5 for a 15 cm² cone)
CPT Engineering Properties
Cohesionless Soils

- Density description
- Relative Density (Dr)
- Angle of Internal Friction ($\phi$)
- SPT equivalent (N)
- Young’s Modulus (E)
- Constrained Modulus (M)

Proposed Correlation of Tip Resistance to Peak Friction Angle for Uncemented Quartz Sands (Robertson and Campanella, 1983)

Variation of $q_c/N$ with Mean Grain Size (Robertson et al, 1983)
Marchetti Dilatometer

Push-in Flat Blade
Minimizes Penetration Disturbance
(ASTM D6635)

Measurements:
• Insitu Lateral Stress
• Modulus
• Shear Strength
• Depth Profile (every 20 to 30 cm)
Marchetti Dilatometer

Uses:
- Settlement
- Slope Stability
- Lateral Stress (walls, tunnels, excavations)
- Compaction Control
- Dissipation Testing, $c_H$

\[ S = \sum \frac{\Delta \sigma_Y}{M_{DMT}} \cdot \Delta z \]

Soil parameters

DMT predicted Settlements

Schmertmann (1988) and Hayes (1988)

DMT reflects more sensitively the compaction benefits and modulus increase
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Top-down Static Load Tests (ASTM D1143)

Design Optimization requires load to failure plus instrumentation
Static Test Instrumentation

- Quick Test: ~20 loads to failure, 5 min load increments
- Redundant load and deflection measurements, reference beams
- Shade / weather protection
- Plot Creep 1-4 min Creep vs. Load to find Creep Limit
- Strain gauges and telltales to develop load transfer diagram
Automated Uni-Directional Testing

- Load control
- Real-time results
- Creep data
- Reduced analysis
Bi-Directional Osterberg Cell Testing

- Specialized jack cast into pile uses bearing beneath it to mobilize side shear above it
- Developed by Dr. Jorj Osterberg and American Equipment
- First commercial test in drilled shaft / bored pile in 1989
- LOADTEST Inc. founded 1991, (purchased by Fugro in 2008)
- Test performed following ASTM D1143 (writing new Standard)
Conventional Test

\[ P = F + Q \]

Osterberg Cell Test

\[ O = F = Q = P/2 \]

\[ O_1 = F_1 = (F_2 + Q) \]
O-cell Instrumentation

- O-cell Expansion Transducers
- O-cell Top Telltales
- Pile Top Deflection
- Pile Bottom Telltales
- Shaft Strain Gauges
- Embedded Shaft Compression Transducers
Side Shear from Strain Gauges

Mobilized Net Unit Side Shear (ksf)

Upward Average Shear Zone Displacement (in)

- S.G. Level 6 to Zero Shear
- S.G. Level 5 to S.G. Level 6
- S.G. Level 3 to S.G. Level 5
- S.G. Level 2 to S.G. Level 3
- O-cell to S.G. Level 2
O-cell Static Load Test Advantages

- Test drilled shafts (wet/dry), CFA piles, driven concrete or steel piles, barrettes
- Separates side shear & end bearing
- Very high load capability
  
  (321MN / 36,000 tons, St. Louis, 2010)
- Direct loading of rock socket
- Cost, safety, and space advantages
- No additional reaction system needed
- Doubles effective jack load
- Post-test grouting for production piles
COMPARISON OF LOAD TESTING COSTS
CONVENTIONAL VS. O-CELL

<table>
<thead>
<tr>
<th>TEST LOAD - MN</th>
<th>COST/ MN</th>
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<tbody>
<tr>
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<td></td>
</tr>
</tbody>
</table>

- Conventional: $500/MN ($4.5/ton)
- O-cell: $500/MN ($4.5/ton)
O-cell Test Limitations

- Shaft preselected
- Maximum load limited by weaker of end bearing or side shear (use multi-level)
- Top of pile not structurally tested
- Must construct equivalent top load movement curve
  - use the sum of measured behavior
  - use the sum of modeled behavior
  - use from finite element, t-z approach
Typical O-cell Test Result

- Upward movement from O-cell as measured
- Downward movement from O-cell as measured
- Maximum O-cell load applied

Displacement (mm) vs. Applied Load (MN)
Equiv. Top-Load + Elastic Shortening

- Measured behaviour curve
  - Modified to include Additional Elastic Compression
High Strain Dynamic Testing

Measure pile force & velocity
Pile Driving Analyzer® PAX
Driven or Cast-in-Place piles
ASTM D4945

For each hammer blow:
– Pile stresses
– Pile integrity
– Hammer performance
– Capacity mobilized at time of test
Use PDA to Measure Driven Pile Setup

SETUP is a continuing increase in side shear due to changes in pore pressure & lateral stresses, and aging effects for all soil types. RELAXATION?

Verify with Restrikes

Baton Rouge, LA, 2008, 610mm Concrete Pile
Baton Rouge Throughway Setup

LA, 2008, 24” Concrete Pile L = 108 ft

Setup RS, kips = $80.6 \log (t, \text{days}) + 397$, $r^2 = 0.99$

Setup RU, kips = $80.6 \log (t, \text{days}) + 542$

Static Test, Max. Load

$A = 0.20$
Crosstown Expressway, HOV, Tampa, FL

3.2 mi, 204 Single-Shaft Piers, 6 ft Dia, 2500 ton Load, 11 ft “Settlement” (2004)
Crosstown Expressway Shafts, Tampa, FL

- 12 Piers Tested
- APE-750U hydraulic hammer, 60 ton ram, 6 ft drop
- "Mother of All Pile Hammers"
- 2 PDA systems used to monitor stress in pier and shaft capacity (4 strains and 4 accel. each)
- $300 mil Project
- Remediation fix for ¾ of piers added ~$100 mil
- Prevented by more testing & investigation?
Reduce Cost by Reducing Uncertainty:

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  - FLT’s experience - savings >5X test cost
- Quality control testing to reduce cost of post-construction remediation
Skyway Bridge, Tampa, FL (1984)

- 4000 ft post-tension span w/ 3+ miles trestle
- Main piers 44 shafts each 5’ dia x 100’, 1000 ton design load
- $3 mil Site Investigation + Static & Dynamic Tests
- 10,000 ft SPT, 1000 ft CPT, 1000 ft DMT, 36 BST, 43 PMT, lab tests
- Two 1000 ton Test Frames
- Shaft Inspection Device to use end bearing saved 25ft per shaft  ~$500 k
Ratio of Measured / Estimated Capacity

One of FLT’s first major discoveries! (How designers handle uncertainty i.e. lower expectations lead to higher costs)

128 = LOADTEST Project Reference no. Schmertmann & Hayes

Soft to Hard Soils  Intermediate  Hard Rock

M/E

15
10
5
1
Ratio of Measured / Estimated Capacity

One of FLT’s first major discoveries!
(How designers handle uncertainty i.e. lower expectations lead to higher costs)

Wasted value due to uncertainty and complacency
LRFD Example

- Simple Non-redundant Foundation Design (uniform site)
- N = 100 shafts
- Length = 100 feet deep, $R = \varphi R_N$
- Unit Cost = $400 / ft
- Cost of Foundation $4,000,000
- Cost of Engineering and Site Investigation $40,000
- Total Cost = $4,040,000 (w/o load test program)
- Cost of Proposed Load Test Program $200,000
- $\varphi = 0.45$ before load test, $\varphi = 0.60$ after load test
- After load test, R increases 33% ($\varphi = 0.45 \rightarrow 0.60$)
- After load test, Length and Total Cost decrease by 25%

But we have ignored the value of the load test result ...
Theoretical Capacity (design)
LRFD Example

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- Cost of Proposed Load Test Program $200,000
- \( \varphi = 0.45 \) before load test, \( \varphi = 0.60 \) after load test
- After load test, \( R_N \) increases 100% & \( R \) increases 33%
- Net effect - \( R \) increases by 2 x 1.33 = 2.66
- After load test, Length and Total Cost decrease by 62.5%
- Foundation Cost = \( ($400/ft)(37.5 \text{ ft})(100 \text{ shafts}) = $1,500,000 \)
- Total Cost = $1,500,000 + 200,000 + 40,000 = $1,740,000
- Net Savings $2,300,000
“Costs” of Testing

Foundation System 1

Includes Basic Engineering and Site Investigation

LRFD, $\varphi = 0.45$
Theoretical Ultimate Cost = $4,040,000

Foundation System 2

Includes Basic Engineering, Site Investigation, and O-cell Testing

LRFD, $\varphi = 0.60$
Actual Ultimate Cost = $1,740,000
(save $2,300,000)
Initial Design
- 9 m Rock Sockets (“typical”)
- Design side shear: 1.3 MPa (code)

O-cell Tests
- 2 Shafts with 1.5 m rock sockets
- Measured side shear: 2.7 MPa

Estimated vs. Actual Costs
- Final design: 4.5 m rock sockets
- Design FS = 3, Measured FS > 5
- Redesign FS > 2
- Fdn. Cost Est.: $18,000,000
- Testing cost: $ 255,000
- Fdn. redesign cost: $ 8,900,000
- Net Savings: $ 8,845,000

Cost Savings: Seacaucus NJ Transfer Sta.
### O-cell Cost Savings

<table>
<thead>
<tr>
<th>Job Number</th>
<th>566</th>
<th>775</th>
<th>835</th>
<th>381</th>
<th>056*</th>
<th>335</th>
<th>426</th>
<th>635</th>
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</thead>
<tbody>
<tr>
<td>State</td>
<td>CA</td>
<td>FL</td>
<td>NC</td>
<td>NJ</td>
<td>SC</td>
<td>GA</td>
<td>TX</td>
<td>FL</td>
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<tr>
<td>Fdn. Estimate</td>
<td>$850</td>
<td>$6,200</td>
<td>$32,500</td>
<td>$18,000</td>
<td>$160,000</td>
<td>$3,270</td>
<td>$8,500</td>
<td>$4,520</td>
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<tr>
<td>Fdn. Redesign</td>
<td>$610</td>
<td>$4,980</td>
<td>$24,500</td>
<td>$8,900</td>
<td>$125,000</td>
<td>$3,003</td>
<td>$8,500</td>
<td>$7,232</td>
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<tr>
<td>Savings</td>
<td>$240</td>
<td>$1,220</td>
<td>$8,000</td>
<td>$9,100</td>
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<td>$273</td>
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<td>Test Cost</td>
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<td>$255</td>
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<td>Net Savings</td>
<td>$161</td>
<td>$855</td>
<td>$6,000</td>
<td>$8,845</td>
<td>$27,500</td>
<td>$33</td>
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<tr>
<td>Measured FS</td>
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<td>3.5</td>
<td>4.0</td>
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<td>Redesign FS</td>
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<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.3</td>
<td>9.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- More than **70%** of the FLT testing saved the client money
- Half of the remaining **30%**, testing done too late to realize the savings
- Only a few estimates were so close not to allow a modified foundation
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Deep Foundation Quality Control

- **Driven Piles**
  - Blow Count, Hammer Energy
- **Drilled Shafts**
  - Control Slurry Properties
  - Prepare Excavation Log
  - Shaft Profile - Sonic Caliper
  - Clean Shaft Bottom
    - MiniSID, Downhole Camera
- **Concrete Quality** - Pile Integrity Test, Crosshole Sonic Logging, Thermal, Gamma
Shaft Profile - SONICALIPER
Shaft Profile - SONICALIPER

Uses sound reflection
360° profile of shaft walls
Checks hole verticality and drift
Real-time results
6 mm Accuracy, 3-D modeling
Portable and compact
Minimal impact to schedule
Shaft Profile Report - SONICALIPER

- Verticality
- Cage Encroachment
- Calculate Concrete Volume

Concrete Volume $V = 127 \text{ yd}^3$
Shaft Volume - SONICALIPER

Theoretical Volume
55 cubic yards
42 cubic meters

Est. Volume via sonicCaliper
132 cubic yards
100 cubic meters

Actual Poured
Concrete Volume
134 cubic yards
102.5 cubic meters

Symmetrical Casing
Bottom of Casing
Protrusion due to "Chasing" Boulder
Shaft Inspection Device, Mini-SID (wet shafts)

- Inspect bottom to check sediments
- Air chamber with video camera
Dirty bottom, Orlando, FL
Soft shaft bottom

O-cell Load-Movement Curves

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**Excess movement to engage end bearing**

(A good reason for load testing)
Mini-SID Video Inspection

Clean (corehole)

Dirty, Clay Lumps

Includes Water Jets & Debris Depth Indicator
Downhole Camera (dry shaft inspection)

Camera rotates and gimbles 180°
Conclusions

- Deep foundation design generally conservative due to uncertainty
- Reduce project cost through a more efficient design that reduces uncertainty
- Use a portion of the cost savings to fund the testing needed for more efficient design

“The owner pays for a good site investigation whether he does one or not.”
Thank You

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www.loadtest.com