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NCHRP Synthesis 478
Design and Load Testing of Large Diameter Open-Ended Driven Piles

A Synthesis of Highway Practice
Objectives

- Understand the key items learned from the synthesis process (literature review and interviews)
- Summarize practices being used by state DOTs, illustrated by case history examples
Objectives

- Key items learned
  - Development and influence of a soil plug in a pile
  - Static analysis methods
  - Drivability issues and criteria
  - Dynamic testing
Objectives

- Key items learned
  - Static testing
- Lessons from outside the transportation sector
Definitions
and
Background
Large Diameter Open Ended Piles (LDOEPs)

- Driven pile
  - Tubular steel
  - Prestressed concrete cylinder
- 36 inches outside diameter or larger
Steel Pipe Piles

- **Spiralweld:** Continuously welded spiral from coiled sheet

- **Rolled and welded:** Plate steel rolled and welded

*photos courtesy Skyline Steel*
Concrete Pipe Piles

- Spun Cast or Bed Cast
- Prestressed
- Post-tensioned

photo courtesy Gulf Coast Prestress
Typical LDOEP Applications

- High lateral load demands (often due to extreme event loading)
- High axial demand
- Deep weak soils
Typical LDOEP Applications

- Eliminate the need for a footing by using a pile bent
- Marine construction - delivery, handling, and installation
- Significant unsupported length (scour, liquefaction, marine conditions)
Unique Challenges of LDOEPs

- Uncertainty of “plug” formation during installation
- Potential for installation difficulties and pile damage during driving is unlike other types of conventional bearing piles
Unique Challenges of LDOEPs

- Soil column within the pile may behave differently during driving or dynamic testing compared with static loading
- Axial resistance from internal friction
- Verification of nominal axial resistance is more challenging and expensive
Key Items Learned From Synthesis Process
Objectives

- **Key items learned**
  - *Development and influence of a soil plug in a pile*
  - Static analysis methods
  - Drivability issues and criteria
  - Dynamic testing
A Simplified Examination of the Dynamic Behavior of a Soil Plug

FIGURE 4 Schematic of a soil plug inside a pipe pile
A Simplified Examination of the Dynamic Behavior of a Soil Plug

- Pile often advances without plugging due to soil plug inertial resistance
- Acceleration of an LDOEP during driving >30g (Stevens, 1988)
- Inside unit side resistance too low to resist accelerations
Objectives

- Key items learned
  - Development and influence of a soil plug in a pile
  - *Static analysis methods*
  - Drivability issues and criteria
  - Dynamic testing
Design for Axial Loading

- Nominal axial resistance determined from driving resistance
- Static computations serve as guide for estimating length
Design for Axial Loading

- Axial Resistance in Clay Soils (“alpha”)
- Axial Resistance in Sands (“beta”)
- Methods Utilizing CPT Data (API RP2 GEO 2011)
- Methods Specific to Prestressed Concrete LDOEPs (FDOT)
Design for Axial Loading

- API RP2 GEO 2011
  - Current state of practice for design for offshore industry
  - Long history of use
  - Slight differences from FHWA “alpha” and “beta” based on offshore experience
  - Several CPT-based methods
    - ICP-05, UWA-05, NGI05, Fugro05
Resistance Factor Selection

- Current (2013) AASHTO guidelines do not specifically represent LDOEPs.

- Based largely on NCHRP Report 507 (Paikowsky (2004))
  - A very small number of open ended pipe piles.
  - LDOEPs are not documented separately from smaller piles.
Design for Lateral Loading and Serviceability

- Not different than for other deep foundations
- Consider contribution to lateral stiffness of concrete plug at top of pile (connection)
- Consider soil plug/column contribution to axial stiffness
Objectives

Key items learned
- Development and influence of a soil plug in a pile
- Static analysis methods
- *Drivability issues and criteria*
- Dynamic testing
Considerations Affecting Behavior of Steel LDOEPS

- Base Resistance of Steel LDOEPs on Rock and Driving Shoes
  - Shoe increases diameter – inside vs. outside
  - Shoe height and buckling of toe
  - Sloping rock
Considerations Affecting Behavior of Steel LDOEPS

- Vibratory Driving and Splicing
- Effect of Pile Length on Behavior and Axial Resistance
  - Reduced side resistance (remolding, friction fatigue, etc.)
  - Elastic compression enduring driving
- Time-Dependency of Axial Resistance
Considerations Affecting Behavior of Steel LDOEPS

- Driving Resistance and Dynamic Load Testing
  - Modeling inertial resistance of the soil plug/column
  - Inserts to promote plugging
  - Residual stresses
  - Limitations of hammer mobilizing resistance
  - Detection and avoidance of pile damage during installation
Considerations Affecting Behavior of Concrete LDOEPS

- Pile volume and prestressed concrete LDOEPs
  - Area ratio vs. steel piles – frictional resistance
  - Potential for plugging
  - Soil “bulking” in void
  - Hoop stress / water hammer
Considerations Affecting Behavior of Concrete LDOEPS

- Base resistance of concrete LDOEPs
  - Plugging vs mobilizing cross-section

- Driving Resistance and Dynamic Load Testing
  - Management of driving stresses
  - Splices rare
Objectives

- Key items learned
  - Static testing
- Lessons from outside the transportation sector
Static Load Testing

- Can be difficult and costly to meet design load for larger piles
- Rapid load test methods (such as Statnamic) becoming common
Objectives

- Key items learned
  - Static testing

- Lessons from outside the transportation sector
Lessons Learned Outside Transportation

- Dr. D. Michael Holloway, P.E. – Consulting Engineer
- Mr. Mike Muchard, P.E. – Applied Foundation Testing, Inc.
- Mr. Steven Saye, P.E. – Kiewit
- Dr. Robert Stevens, P.E. – Fugro-McClelland Marine Geosciences, Inc
- Mr. Scott Webster, P.E. – GRL Engineers, Inc.
Lessons Learned Outside Transportation

Pile Plugging (or absence of plugging):

- Dominates pile driving behavior
- Difficult to predict
- Treated as choice of plugged or unplugged – actual behavior is in between the two
- General consensus is driving occurs unplugged for most piles
Lessons Learned Outside Transportation

Dynamic Testing Issues:

- Effect of plug behavior on dynamic testing and data interpretation
- Demonstrating full resistance for high loads
- Instrument location and quantity more critical
- Accounting for residual stress from manufacturing
- Pile durability due to trying to achieve high loads
Lessons Learned Outside Transportation

Static Axial Analysis:

- Most widely used methods significantly underestimate pile resistance
- API RP2 GEO from offshore industry consider good predictor of resistance
- Lack of accounting for residual stress
Summary of Current State DOT Practices
Summary of Current State DOT Practices

Survey of 50 State DOTs, District of Columbia, Puerto Rico

18 Agencies indicated LDOEP experience

NCDOT and MaineDOT are in design phase only (no construction experience)
Summary of Current State DOT Practices

- Report focused on responses of the 16 with design and installation experience.
- Telephone interviews with 7 agencies (Bold in red)
  - Most experience
  - Represent different geographic areas and geologic conditions

<table>
<thead>
<tr>
<th>LDOEP Experience</th>
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</thead>
<tbody>
<tr>
<td>Alabama (ALDOT)</td>
<td>Louisiana (LADOTD)</td>
</tr>
<tr>
<td>Alaska (ADOTPF)</td>
<td>Massachusetts (MassDOT)</td>
</tr>
<tr>
<td>California (Caltrans)</td>
<td>Maryland DOT</td>
</tr>
<tr>
<td>Florida (FDOT)</td>
<td>Minnesota (MnDOT)</td>
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<tr>
<td>Idaho (Idaho DOT)</td>
<td>New York (NYSDOT)</td>
</tr>
<tr>
<td>Illinois (Illinois DOT)</td>
<td>Ohio (ODOT)</td>
</tr>
<tr>
<td>Iowa (Iowa DOT)</td>
<td>Texas (TXDOT)</td>
</tr>
<tr>
<td>Kentucky (KYTC)</td>
<td>Virginia DOT</td>
</tr>
</tbody>
</table>
Reasons DOTs are NOT using LDOEPs:

- Not cost-competitive
- Geologic and soil conditions more suited to other
- Lack of expertise and equipment among contractor pool
- Small typical structure size and loads.
- Design not specifically addressed in AASHTO
Summary of Current State DOT Practices

Reasons DOTs are NOT using LDOEPs:

- Specific design issues and questions:
  - Prediction and extent of plugging
  - Determining pile capacity/resistance
  - Length of concrete infill
  - Structural design of concrete-steel section
  - Resistance factor selection
- Concerns over vibrations to adjacent structures.
Summary of Current State DOT Practices

10. What are the static analysis methods used by your agency to determine nominal axial resistance and displacements for LDOEPs in cohesionless soils? (check all that apply)

- Meyerhof SPT (FHWA 2006): 12.5%
- Nordlund (FHWA 2005): 62.5%
- Brown (FHWA 2005): 12.5%
- Effective Stress - Beta (FHWA 2006): 18.8%
- Method based on Cone Penetration Test: 18.8%
- In-House Method: 25%
- Other: 31.3%

11. What are the static analysis methods used by your agency to estimate nominal axial resistance and displacements for LDOEPs in cohesive soils? (check all that apply)

- alpha (Tomlinson) (FHWA 2006): 62.5%
- Effective Stress - Beta (FHWA 2006): 50%
- Method based on Cone Penetration Test: 18.8%
- In-House Method: 25%
- Other: 31.3%
Summary of Current State DOT Practices

In-house or other methods:

- ADOTPF: modified Beta method from historic dynamic testing (Dickenson, 2012).
- ALDOT: Computer program from test pile data
- FDOT: Software FBDEEP developed by Univ. of Florida
- IDOT: Modified IDOT Static Method (correlations with SPT $N_{(1)60}$ and $q_u$)
- TXDOT: Texas Cone Penetrometer correlations
- Caltrans and KYTC: API Method
## Summary of Current State DOT Practices

### Resistance Factor Selection

<table>
<thead>
<tr>
<th>Resistance Factor Selection</th>
<th>Percentage</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current AASHTO Specifications</td>
<td>50.0%</td>
<td>8</td>
</tr>
<tr>
<td>My Agency Developed Factors</td>
<td>12.5%</td>
<td>2</td>
</tr>
<tr>
<td>Combination of AASHTO and My Agency</td>
<td>31.3%</td>
<td>5</td>
</tr>
<tr>
<td>Other Agency or source</td>
<td>6.3%</td>
<td>1</td>
</tr>
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</table>
### Driving Criteria

<table>
<thead>
<tr>
<th>Description</th>
<th>Percentage</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive to a specified tip elevation</td>
<td>18.8%</td>
<td>3</td>
</tr>
<tr>
<td>Drive to a minimum tip elevation</td>
<td>56.3%</td>
<td>9</td>
</tr>
<tr>
<td>Drive to practical refusal</td>
<td>18.8%</td>
<td>3</td>
</tr>
<tr>
<td>Drive to a specified driving resistance (blow count) based on a driving formula</td>
<td>6.3%</td>
<td>1</td>
</tr>
<tr>
<td>Drive to a specified driving resistance (blow count) based on a wave equation analysis</td>
<td>43.8%</td>
<td>7</td>
</tr>
<tr>
<td>Drive to a specified driving resistance (blow count) based on high strain dynamic tests performed on indicator or test piles</td>
<td>75.0%</td>
<td>12</td>
</tr>
<tr>
<td>Drive to a specified driving resistance (blow count) based on static or rapid load tests performed on indicator or test piles, through signal match and wave equation.</td>
<td>43.8%</td>
<td>7</td>
</tr>
<tr>
<td>Verify resistance with restrikes</td>
<td>62.5%</td>
<td>10</td>
</tr>
</tbody>
</table>
Summary of Current State DOT Practices

Driving Criteria and Testing:

- Majority use wave equation analysis and/or high strain dynamic testing
- Static, Rapid, and Dynamic load tests very common
- Concerns with analysis of high strain dynamic data, particularly with treatment of soil plug/column
- Difficult to mobilize full resistance of large diameter steel piles on rock
Case Histories

- Hastings Bridge, Minnesota
- St. George Island Bridge, Florida
Case Histories – Hastings Bridge, MN

Key issues:
- Increased reliability through demonstrated pile resistance
- Vibrations on existing structures
Key issues:

- Limitations of dynamic tests to demonstrate fully mobilized pile resistance for piles driven to refusal on rock

- Use of lateral load test for design
Case Histories – Hastings Bridge, MN

- 42-in open-end pipe piles
  - $t_w = 1$ inch (for impact loads) or 7/8-in
  - Driven to bear on rock

- Axial Statnamic tests
  - 4,600 kips (1 in); 4,200 kips (7/8 in)
  - Maximum deflection about 2-½ inches; permanent sets of around ¼ in.

- Dynamic tests
  - 3,000 to 3,500 kips (Maximum hammer could mobilize)
Statnamic tests used as basis of design

Dynamic tests utilized on production piles to demonstrate:
- that the piles were driven to a good seating on rock
- that the piles were not damaged
- that the hammer was performing as intended.
Case Histories – St. George Island, FL

Key issues:

- Assess nominal resistance of underlying Florida limestone
- Determining pile order lengths to meet schedule
- Comparison of axial load testing methods
- Control of longitudinal cracking
Case Histories – St. George Island, FL

Testing Program:
- 4 static load tests
- 6 Statnamic load tests
- 50 dynamic tests on production piles
Case Histories – St. George Island, FL

Summary of test results for St. George Island Bridge
(Kemp and Muchard, 2007)

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Static Load Test Maximum Capacity (kN/tons)</th>
<th>STATNAMIC Load Test Maximum Capacity (kN/tons)</th>
<th>CAPWAP Restrike Maximum Capacity (kN/tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-1</td>
<td>9,493 / 1,068</td>
<td>9,627 / 1,083</td>
<td>8,667 / 975</td>
</tr>
<tr>
<td>LT-2</td>
<td>13,813 / 1,554</td>
<td>13,564 / 1,526</td>
<td>8,960 / 1,008</td>
</tr>
<tr>
<td>LT-3</td>
<td>13,600 / 1,530</td>
<td>13,831 / 1,556</td>
<td>8,089 / 910</td>
</tr>
<tr>
<td>LT-5</td>
<td>12,836 / 1,444</td>
<td>11,689 / 1,315</td>
<td>9,013 / 1,014</td>
</tr>
</tbody>
</table>

- Reasonable agreement between static and Statnamic
- Dynamic tests slightly under-predict vs. static
Longitudinal cracks were observed in 7% of piles, usually within three to four weeks after driving.

Determined to be “water hammer” from build-up of fluid soil inside the pile annulus.

Excess “hoop stresses” resulted in cracking.

Contractor elected to monitor and clean out plug/soil column - no further cracking.
Research Needs

- Develop new methods or improve existing methods for calculating static resistance by accounting for the large pile sizes.
- Develop appropriate resistance factors.
- Better understanding of the mechanism of pile plugging, including effectiveness of forcing a pile to plug.
Research Needs

- Determining the most appropriate or applicable failure criteria/mechanism.
- Calibration of resistance factors and static analyses methods to dynamic testing.
- Guidance on how to adequately perform signal matching and wave equation analysis for LDOEPS as compared to smaller piles.
Questions?

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