Soil/Pile Set-Up in Driven-Pile Foundation Design and Installation

Pile Driving Contractors Association
2015 Professor’s Driven Pile Institute

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Talk Outline

• Overview (definition and mechanisms)
• Determination
  – Estimation accuracy scenarios
• Time Rate
• Shaft set-up profile (case history)
  • Unit shaft set-up profile
  • Cumulative shaft set-up profile
  – Depth variable driving criteria, for multiple allowable loads
  – Cost-effectiveness illustrations
Set-Up Overview

- Time-depandant capacity increase
- Predominantly related to increased shaft resistance due to dissipation of driving-induced excess porewater pressures
- Related to pile properties (size, type), & soil properties (composition, strength/relative density, effective stress, permeability, plasticity, overconsolidation ratio, etc.)
- Empirical relationships limited in applicability
- Site-specific test programs most-valuable way to characterize set-up
Set-Up Overview

- Set-up can provide significant contribution to long-term pile capacity

- Benefits include:
  - Smaller hammers
  - Smaller pile sections
  - Shorter piles
  - Higher capacities
  - More-economical installations

- Benefits of characterizing cumulative shaft set-up profile:
  - Produce depth-variable criteria, multiple allowable loads
  - Evaluate hammers, sections, capacities, & depths
  - Apply different safety factors to initial capacity & set-up
  - Assign reduced capacities to short or damaged piles
    (may preclude requiring additional piles)
Talk Outline

- **Overview** (definition and mechanisms)
- **Determination**
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- **Time Rate**
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  - Unit shaft set-up profile
  - Cumulative shaft set-up profile
  - Depth variable driving criteria, for multiple allowable loads
  - Cost-effectiveness illustrations
Dynamic Testing Capacity Estimation

Accuracy

- Blow count too high (approximately $>120$ bpf): Soil is not failed, capacity is not mobilized/activated; capacity is underestimated. Analogous to running out of jack capacity before plunging failure for a static load test. “Move it to prove it.”

- Blow count too low (approximately $<30$ bpf): Soil/pile system is moving so fast that dynamic analysis methods have difficulty differentiating static and dynamic (inertia effects) capacity; capacity is overestimated.
## Set-Up Determination Accuracy Scenarios

<table>
<thead>
<tr>
<th>End-Of-Initial-Drive Capacity</th>
<th>Long-Term Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially Under-Estimated  (bpf&gt;120)</td>
<td>Set-Up Potentially Underestimated</td>
</tr>
<tr>
<td>Potentially Over-Estimated (bpf&lt;30)</td>
<td>Set-Up Potentially Underestimated</td>
</tr>
<tr>
<td>Reasonably Estimated (30&lt;bpf&lt;120)</td>
<td>Set-Up Potentially Underestimated</td>
</tr>
<tr>
<td>Potentially Under-Estimated (bpf&gt;120)</td>
<td>Set-Up Potentially Indeterminate</td>
</tr>
</tbody>
</table>
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Shaft Set-Up Rate
Shaft Set-Up Rate

![Chart showing shaft set-up rate over time. The chart displays a linear relationship between time and set-up rate. At 60 Tons, the time since EOID is approximately 1.0 days (on a log scale).]
Shaft Set-Up Rate

![Graph showing the relationship between time and shaft set-up rate. The graph is linear and shows an increase in shaft set-up rate with time. A vertical line at 60 tons intersects the graph at a specific time point, indicating the rate at which the shaft set-up increases over time.](image)
Shaft Set-Up Rate

- 60 Tons in 10 Days
- 60 Tons
- 47 Tons in 50 Days
- 120 Tons in 10 Days
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Lake Pointe Tower
## Lake Pointe Tower

<table>
<thead>
<tr>
<th>Distance from Z-Axis, ft</th>
<th>Pile Row Number</th>
<th>Combined Pile Loads from All Sources, tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.00</td>
<td>64.00</td>
<td>66.00</td>
</tr>
<tr>
<td>62.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>64.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>66.00</td>
<td>2.00</td>
<td>2.00</td>
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<tr>
<td>68.00</td>
<td>2.00</td>
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<tr>
<td>70.00</td>
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<tr>
<td>72.00</td>
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<td>2.00</td>
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<tr>
<td>74.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>76.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

### Color Legend:

- 1: 300 to 315 Tons
- 2: 275 to 300 Tons
- 3: 250 to 275 Tons
- 4: 225 to 250 Tons
- 5: 200 to 225 Tons
- 6: 175 to 200 Tons
- 7: 150 to 175 Tons
- 8: 125 to 150 Tons
- 9: 100 to 125 Tons
- 10: 75 to 100 Tons

* Based on steel compatibility between steel shell and concrete mix.
### Soil Description

<table>
<thead>
<tr>
<th>Elevation (feet, Milwaukee City Datum)</th>
<th>Soil Description</th>
<th>Blows / Foot N</th>
<th>Unconfined Compressive Strength, tsf</th>
<th>General Soil Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>-145</td>
<td>Silt, trace sand &amp; gravel</td>
<td>109</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-135</td>
<td>Fine sand</td>
<td>55</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-125</td>
<td>Sandy silt, little gravel</td>
<td>88</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-115</td>
<td>Silty clay, trace to little sand &amp; gravel</td>
<td>65</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-105</td>
<td>Very sandy silt, little silt</td>
<td>52</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-95</td>
<td>Fine to coarse sand, little silt</td>
<td>32</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-85</td>
<td>Very sandy silt, trace clay</td>
<td>27</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td>Clayey fine sand to sandy clay</td>
<td>22</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-65</td>
<td>Clayey to silty fine sand</td>
<td>13</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-55</td>
<td>Silty clay, little to trace sand &amp; gravel</td>
<td>19 - 23</td>
<td>1.5 - 2.5</td>
<td>Cohesionless</td>
</tr>
<tr>
<td>-45</td>
<td>Clayey silt to sandy silt</td>
<td>15</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>-35</td>
<td>Silty clay, trace sand &amp; gravel with silt seams and layers</td>
<td>8 - 13</td>
<td>1.5 - 3.5</td>
<td></td>
</tr>
<tr>
<td>-25</td>
<td>Fill: Sand</td>
<td>5 to 28</td>
<td>—</td>
<td>Fill</td>
</tr>
</tbody>
</table>

### General Soil Characteristic

- **Cohesive**
- **Fine-Grained Cohesionless**
Lake Pointe Tower

• Three different closed-end pipe piles considered:
  - 12.75-inch-O.D. x 0.375-inch wall
  - 14-inch-O.D. x 0.500-inch wall
  - 16-inch-O.D. x 0.500-inch wall

• Test pile program for structure
  - Test piles dynamically monitored at end-of-initial-drive ("EOID") and beginning-of-restrike ("BOR")
  - CAPWAPs performed on EOID and BOR data
  - Internally-instrumented static load test
Lake Pointe Tower Test Program

• 7 test piles, 1 statically load tested (16-inch)

• Hammers
  - Installation: Delmag D46-32 single-acting diesel, 107.2 ft-kips (manufacturer’s maximum rated energy)
  - Restrike: GRL APPLE drop hammer, with 20-ton ram, 388 ft-kips maximum energy

• Embedded lengths: 115.8 to 147.3 feet

• EOID penetration resistances: 21 to 69 blows per foot
Driving Behavior
Lake Pointe Tower - Case-Method Initial Ultimate Capacity vs. Pile Toe Elevation - 16-Inch Piles

Case-Method Initial Ultimate Capacity, tons

Pile Toe Elevation, feet (Milwaukee City Datum)

Fill
Cohesive
Fine-Grained Cohesionless
Fine-Grained Cohesionless
Cohesive

CASE-Method Initial-Drive Capacity
Lake Pointe Tower - End-Of-Initial-Drive
CAPWAP Unit Shaft Resistance vs. Elevation -
16-Inch Piles

EOID CAPWAP
Unit Shaft
Resistance
Profiles
Lake Pointe Tower - Beginning-Of-Restrike
CAPWAP Unit Shaft Resistance vs. Elevation -
16-Inch Piles

BOR CAPWAP
Unit Shaft
Resistance
Profiles
Unit Shaft Set-Up Profile Determination

BOR Unit Shaft Resis.

EOID Unit Shaft Resis.

Unit Shaft Resistance, pounds per square foot

Elevation, feet (Milwaukee City Datum)
Lake Pointe Tower - Estimated Ultimate Cumulative Shaft Set-Up vs.
Pile Toe Elevation - 16-Inch Piles

- Static Load Test Pile - 16x0.500 - 39.174 Days (60/384)
- Northwest Anchor Pile - 16x0.500 - 44.715 Days (48/384)
- Southeast Anchor Pile - 16x0.500 - 41.636 Days (48/384)

Cumulative Shaft Set-Up Profiles
For a 16-inch-diameter pile, 5,000 psf set-up = 10 tons per linear foot
Lake Pointe Tower - Estimated Ultimate Cumulative Shaft Set-Up vs. Pile Toe Elevation - 16-Inch Piles

- Static Load Test Pile - 16x0.500 - 39.174 Days (60/384)
- Northwest Anchor Pile - 16x0.500 - 44.715 Days (48/384)
- Southeast Anchor Pile - 16x0.500 - 41.636 Days (48/384)
- Resulting From Design Unit Shaft Set-Up Profile - 16-Inch Piles

Cumulative Shaft Set-Up Profiles
Long-Term Capacity Profile Determination

Case-Method EOID Capacity

Cumulative Set-Up

Estimated Ultimate Capacity, tons

Estimated Ultimate Capacity, tons
Lake Pointe Tower - Estimated Ultimate Capacity vs. Pile Toe Elevation - Northwest Anchor Pile (16-inch)

- Case-Method Initial Capacity
- Cumulative Shaft Set-Up Capacity
- Long-Term Capacity (Initial Plus Cumulative Shaft Set-Up)

Elev. -116: Set-Up is 80% of Long-Term Capacity

Long-Term Capacity Profile
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Lake Pointe Tower - Estimated Ultimate Capacity vs. Pile Toe Elevation - Northwest Anchor Pile (16-inch)

- Case-Method Initial Capacity
- Cumulative Shaft Set-Up Capacity
- Long-Term Capacity (Initial Plus Cumulative Shaft Set-Up)

Long-Term Capacity Profile
Lake Pointe Tower - Required Initial Capacity Profile Determination - 16-Inch Piles - 350 Tons Allowable/700 Tons Ultimate

Ultimate Capacity, tons

Pile Toe Elevation, feet (Milwaukee City Datum)

- Required Long-Term Ultimate Capacity (350 Tons Allowable/700 Tons Ultimate)
- Design Cumulative Shaft Set-Up Profile - 16-Inch Piles

Set-Up

Required Initial for 700 tons

Pile Toe (Elev. -90)
Lake Pointe Tower - Required Initial Capacity Profile
Determination - 16-Inch Piles - 300 Tons Allowable/600 Tons Ultimate

- Required Long-Term Ultimate Capacity (300 Tons Allowable/600 Tons Ultimate)
- Design Cumulative Shaft Set-Up Profile - 16-Inch Piles

Ultimate Capacity, tons

Pile Toe Elevation, feet (Milwaukee City Datum)

Set-Up

Required Initial for 600T (Ultimate)

Pile Toe (Elev. -90)
Lake Pointe Tower - Required Initial Capacity Profile
Determination Example - 16-Inch Piles

- Required Initial Capacity (350 Tons Allowable/700 Tons Ultimate)
- Required Initial Capacity (300 Tons Allowable/600 Tons Ultimate)
## Depth-Variable Criteria

<table>
<thead>
<tr>
<th>Embedded Depth, feet</th>
<th>Minimum Required Penetration Resistance, blows per foot (bpf)</th>
<th>Hammer Stroke, feet (Highest (#4) Fuel Setting)</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
<th>8.5</th>
<th>9.0</th>
<th>9.5</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
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</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
<td>7.0</td>
<td>7.5</td>
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<td>8.5</td>
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<td>deeper</td>
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<td>25</td>
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<td>16</td>
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<td>13</td>
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</tr>
</tbody>
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Capacity Profiles

16-inch-O.D. closed-end pipe: $65.00 per foot

**Without Set-Up**

<table>
<thead>
<tr>
<th>Testing</th>
<th>Allowable Load, tons</th>
<th>Pile Support Cost, dollars per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (SF=3.0)</td>
<td>113</td>
<td>$68.45</td>
</tr>
<tr>
<td>Dynamic (SF=2.5)</td>
<td>136</td>
<td>$56.88</td>
</tr>
<tr>
<td>Static (SF=2.0)</td>
<td>170</td>
<td>$45.50</td>
</tr>
</tbody>
</table>

**With Set-Up**

<table>
<thead>
<tr>
<th></th>
<th>Allowable Load, tons</th>
<th>Pile Support Cost, dollars per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Dynamic (SF=2.5)</td>
<td>312</td>
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<tr>
<td></td>
<td>Static (SF=2.0)</td>
<td>390</td>
</tr>
<tr>
<td>3</td>
<td>Dynamic (SF=2.5)</td>
<td>404</td>
</tr>
<tr>
<td></td>
<td>Static (SF=2.0)</td>
<td>505</td>
</tr>
</tbody>
</table>
Closed-End Pipe Concrete Fill Benefit

**TIME**

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Initial</th>
<th>Change</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotechnical</td>
<td>Relatively Low</td>
<td>Set-Up</td>
<td>Relatively High</td>
</tr>
<tr>
<td>Structural</td>
<td>Relatively Low (Steel Shell Only)</td>
<td>Concrete Fill</td>
<td>Relatively High (Steel &amp; Concrete Composite Section)</td>
</tr>
</tbody>
</table>
Closed-End Pipe Concrete Fill Benefit

Structural capacity derived from both steel (expensive) and concrete (inexpensive)

\[ 16 \times 0.500 \]
\[ A_s = 24.35 \text{ in}^2 \]

Structural capacity derived only from steel (expensive)

\[ 16 \times 1.350 \]
\[ A_s = 62.13 \text{ in}^2 \]
Conclusions

- Set-up can account for significant portion of long-term capacity (up to 80% in case history)
- Accounting for set-up in design and installation offers numerous benefits: smaller hammers, smaller pile sections, shorter piles, higher capacities, and more-economical installations
- Characterizing cumulative shaft set-up profiles allows for depth-variable driving criteria for numerous allowable loads
- Estimated initial and long-term capacity profiles can be used to evaluate potential production-pile sections, select cost-effective allowable loads, estimate installed lengths
- Approach allows application of separate (different) safety factors to EOID and set-up capacity components
Never, ever, anger the backhoe operator.

Any other questions/comments?