EVALUATION OF NON-CONFORMING PILES
TOPICS

- Minimum Tip Elevation
- Required Driving Resistance
- Geometrical Tolerance
- Pile Damage
MINIMUM TIP ELEVATION

- Minimum tip elevation most often set to provide fixity at the pile toe

- Highly variable subsurface conditions can be impediments to reaching minimum tip

- NCDOT: US 421 Bridge over Fishing Creek
  - Emergency project after Hurricane washed out the roadway

- Scenario to consider: Many piles do not reach minimum tip elevation
US 421 AT FISHING CREEK AFTER HURRICANE FLORENCE

- Roadway badly damaged
- Emergency design requested by NCDOT
- Partially inaccessible for drill rig access
BORING LOCATION PLAN
SUBSURFACE VARIABILITY

Boring B1_NBL

Boring B2_NBL
PARALLEL 7 SPAN BRIDGES OVER FISHING CREEK
20” SQUARE PRESTRESSED CONCRETE PILES

- NCDOT typically requires short (3 ft) HP stingers for concrete piles driven in hard driving conditions

- HP stingers only considered as toe protection, not used in design
As-Built Pile Tip Elevations
US 421 Left Lane Bridge

As-Built Pile Tip Elevations
US 421 Right Lane Bridge

- 3' Long Steel Stinger
- 20" Sq. PS Concrete Pile
As-Built Pile Tip Elevations
US 421 Left Lane Bridge

Min Tip El. -45 ft

As-Built Pile Tip Elevations
US 421 Right Lane Bridge

3' Long Steel Stinger
20" Sq. PS Concrete Pile
CAPWAP SUMMARY
BENT 2 PILE 5

- HP stinger showing ~123 kips of resistance at 10.7 ksf unit skin friction

- API RP2A guidelines for siliceous sand indicate maximum 2.4 ksf unit skin friction for very dense sand and gravel

- 8+ ksf likely limestone

<table>
<thead>
<tr>
<th>Depth Below Grade</th>
<th>Unit Resist. (Depth)</th>
<th>Unit Resist. (Area)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 ft</td>
<td>2.68 kips/ft</td>
<td>0.40 ksf</td>
<td></td>
</tr>
<tr>
<td>6.8 ft</td>
<td>3.74 kips/ft</td>
<td>0.56 ksf</td>
<td></td>
</tr>
<tr>
<td>9.8 ft</td>
<td>3.14 kips/ft</td>
<td>0.47 ksf</td>
<td></td>
</tr>
<tr>
<td>12.8 ft</td>
<td>2.84 kips/ft</td>
<td>0.43 ksf</td>
<td></td>
</tr>
<tr>
<td>15.8 ft</td>
<td>3.74 kips/ft</td>
<td>0.56 ksf</td>
<td></td>
</tr>
<tr>
<td>18.8 ft</td>
<td>4.07 kips/ft</td>
<td>0.61 ksf</td>
<td></td>
</tr>
<tr>
<td>21.8 ft</td>
<td>3.54 kips/ft</td>
<td>0.53 ksf</td>
<td></td>
</tr>
<tr>
<td>24.8 ft</td>
<td>3.47 kips/ft</td>
<td>0.52 ksf</td>
<td></td>
</tr>
<tr>
<td>27.8 ft</td>
<td>3.10 kips/ft</td>
<td>0.47 ksf</td>
<td></td>
</tr>
<tr>
<td>30.8 ft</td>
<td>3.10 kips/ft</td>
<td>0.47 ksf</td>
<td></td>
</tr>
<tr>
<td>33.8 ft</td>
<td>1.70 kips/ft</td>
<td>0.26 ksf</td>
<td></td>
</tr>
<tr>
<td>36.8 ft</td>
<td>1.70 kips/ft</td>
<td>0.26 ksf</td>
<td></td>
</tr>
<tr>
<td>39.9 ft</td>
<td>3.31 kips/ft</td>
<td>0.50 ksf</td>
<td></td>
</tr>
<tr>
<td>42.9 ft</td>
<td>3.78 kips/ft</td>
<td>0.57 ksf</td>
<td></td>
</tr>
</tbody>
</table>

3 ft long HP stinger ->>

179.86

46.4 40.99 10.70
DRIVING LOG
BENT 2 PILE 5

- HP stinger appears to be embedded in very dense materials
- Reasonable assumption of at least 3 ft of limestone at the toe of the pile
- Inspector driving logs recording blows per ft critical to this evaluation

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Blows Per Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>73</td>
</tr>
<tr>
<td>27</td>
<td>62</td>
</tr>
<tr>
<td>28</td>
<td>78</td>
</tr>
<tr>
<td>29</td>
<td>68</td>
</tr>
<tr>
<td>30</td>
<td>68</td>
</tr>
<tr>
<td>31</td>
<td>79</td>
</tr>
<tr>
<td>32</td>
<td>139</td>
</tr>
<tr>
<td>34</td>
<td>180</td>
</tr>
<tr>
<td>35</td>
<td>180</td>
</tr>
<tr>
<td>36</td>
<td>180</td>
</tr>
<tr>
<td>37</td>
<td>120</td>
</tr>
<tr>
<td>38</td>
<td>119</td>
</tr>
<tr>
<td>39</td>
<td>129</td>
</tr>
<tr>
<td>40</td>
<td>180</td>
</tr>
<tr>
<td>41</td>
<td>191</td>
</tr>
<tr>
<td>42</td>
<td>343</td>
</tr>
<tr>
<td>43</td>
<td>194</td>
</tr>
<tr>
<td>44</td>
<td>289</td>
</tr>
</tbody>
</table>

Very hard driving last ~ 4 ft ->>
AS-BUILT LPILE ANALYSIS
BENT 2

Model as very weak Limestone ->>
TOPICS

- Minimum Tip Elevation
- Required Driving Resistance
- Geometrical Tolerance
- Pile Damage
REQUIRED DRIVING RESISTANCE

- Insufficient axial resistance at the final pile tip elevation

- Common problem with PS concrete piles in coastal geology, particularly when splicing is not allowed

- NCDOT: Bonner Bridge Replacement project

- Scenario to consider: A few piles have insufficient axial resistance but others have excess resistance
REQUIRED DRIVING RESISTANCE – POTENTIAL SOLUTIONS

- Evaluate actual pile loading against PDA test data and pile driving logs rather than applying maximum pile load to all piles
  - Driving resistance can be estimated from pile driving logs using a refined wave equation analysis in GRLWEAP

- Calibrate axial stiffness of soils (T-Z and Q-Z) curves such that the load on the pile is limited to the driving resistance from PDA or driving logs

- Superposition of skin friction and end bearing for displacement piles
ACTUAL PILE LOAD DISTRIBUTION
ACTUAL PILE LOAD DISTRIBUTION
ACTUAL PILE LOAD DISTRIBUTION
**AXIAL STIFFNESS CALIBRATION**

- FB MultiPier was used to model soil structure interaction of pile groups
- Lateral, axial, and rotational spring stiffness of soils modeled in FB MultiPier
- PDA test results can be used to validate or modify the spring stiffness of as-built conditions
AXIAL SOIL SPRING PARAMETERS (T-Z AND Q-Z)

- Driven Pile (McVay) T-Z and Q-Z models utilized

- T-Z inputs: ultimate unit side friction, Poisson’s ratio, shear modulus

- Q-Z inputs: ultimate tip resistance, Poisson’s ratio, shear modulus

- High confidence in ultimate values, low confidence in shear modulus values based on routine test methods
TIP SOIL SPRING (Q-Z)

**Figure: 12.5.a** Q-Z Curve for Driven Pile

Reference FB MultiPier Help Manual
AXIAL STIFFNESS CALIBRATION

3,000 kips  2,800 kips  2,500 kips

= ?
AXIAL STIFFNESS CALIBRATION

3,000 kip  2,800 kips  2,500 kips
AXIAL STIFFNESS CALIBRATION

3,000 kips  2,800 kips  2,500 kips

=
AXIAL STIFFNESS CALIBRATION

- Bridge designer to evaluate revised stresses and displacements of pier cap to determine if they are acceptable
CALIBRATION OF TIP SPRINGS

- Shear modulus values are difficult to reliably estimate.

- Small strain stiffness measurements such as shear wave velocity testing needed.

- How to evaluate shear modulus of a soil plug at the toe of a displacement pile? The in-situ measurements are NOT representative of final stress state of soil.

- Calibrate Q-Z springs such that individual max pile loads are limited to measured values.

Figure: 12.5a Q-Z Curve for Driven Pile
AXIAL STIFFNESS CALIBRATION

- Soften tip spring stiffness on piles with less axial resistance (red and green) until the modeled load on these piles is less than or equal to PDA measured resistance
  - Iteratively revise shear modulus and ultimate tip capacity if needed

- Pile with highest axial resistance (blue) will attract more load to compensate for softer springs at red and green
  - Determine if revised increased load on this pile is acceptable based on PDA measurements

- **Consequence:** The cap will rotate and deflect, generating differing stress distribution. Bridge designer must evaluate increased cap stress and deformation.
SUPERPOSITION OF SKIN FRICTION / END BEARING

- Potential for insufficient driving resistance due to high pore pressures at end of initial drive.

- Restrikes often show higher skin friction, but can show less end bearing than end of initial drive.

- Decrease in end bearing could be due to relaxation or likely due to **insufficient hammer energy** to mobilize tip resistance with increased skin friction due to setup.

- Static load testing with indicator pile proved relaxation is not an issue.
SUPERPOSITION OF SKIN FRICTION / END BEARING

- End bearing may be fully mobilized at end of initial drive with limited skin friction due to pore pressure buildup.

- On restrike pore pressures dissipated so skin friction increases, but hammer energy may be too low to mobilize end bearing.

- Superposition combines skin friction at beginning of restrike with end bearing at end of restrike or at end of initial drive.

<table>
<thead>
<tr>
<th>Time of PDA</th>
<th>CAPWAP Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Skin Resistance, kips</td>
</tr>
<tr>
<td>EOID</td>
<td>880</td>
</tr>
<tr>
<td>14 Day BOR</td>
<td>1850.1</td>
</tr>
<tr>
<td>14 Day EOR</td>
<td>1303</td>
</tr>
</tbody>
</table>

Bent 74
TOPICS

- Minimum Tip Elevation
- Required Driving Resistance
- Geometrical Tolerance
- Pile Damage
Large diameter battered piles in marine environments very difficult to position with tight geometrical tolerances

- +/- 3 inches horizontal tolerance is typical

- +/- 6 inches horizontal tolerance is more reasonable for large diameter piles

- Large number of piles out of +/- 3 inch horizontal tolerance
HORIZONTAL TOLERANCE - RESOLUTION

- Most piles ended up within +/- 6 inches of horizontal position
  - Typical solution was to adjust reinforcing steel in cap and add ‘filler’ reinforcement so there no large unreinforced gaps in the pile caps

- FB MultiPier models typically updated with as-built pile positions and batter angles
  - Small adjustment in horizontal position makes little difference in pile loading and structure behavior
  - Adjustment to batter angle tends to distribute pile load differently

- Precast pile caps require tight geometric tolerance to fit, field adjustment is not possible
  - Very stout frame used to position cylinder piles with precast caps
TOPICS

- Minimum Tip Elevation
- Required Driving Resistance
- Geometrical Tolerance
- Pile Damage
PILE DAMAGE

- Surficial spalling is typical on concrete piles and often does not affect pile integrity and can be repaired in place.

- Structural pile damage typically determined by change in cross sectional area of pile.

- Beta (BTA) method refers to %change in pile impedance in PDA records to evaluate damage.

\[ \text{Impedance} = \frac{EA}{c} \]

- \( C \) (wavespeed) is known for the material type, \( E \) (modulus) is assumed constant, so a change in impedance suggests a change in \( A \) (cross sectional area).
PILE DAMAGE GUIDELINES

- FHWA Design and Construction of Driven Pile Foundations provides the following table to evaluate extent of pile damage based on BTA values from PDA testing.

Table 10-2  Pile Damage Guidelines (after Rausche and Goble 1979)

<table>
<thead>
<tr>
<th>BTA</th>
<th>Severity of Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Undamaged</td>
</tr>
<tr>
<td>0.8 – 1.0</td>
<td>Slightly Damaged</td>
</tr>
<tr>
<td>0.6 – 0.8</td>
<td>Damaged</td>
</tr>
<tr>
<td>Below 0.6</td>
<td>Broken</td>
</tr>
</tbody>
</table>
CYLINDER PILE SURFICIAL DAMAGE

- Damage to pile top was surficial only
- Damaged portion cut off after driving
CYLINDER PILE
STRUCTURAL DAMAGE

- Impedance change (damage) starting approximately 86.9 ft below grade and extending to approximately 113.7 ft below grade

- Assume complete section loss due to 93.9% impedance reduction

- No moment capacity below 86.9 ft
  - Pile fixity achieved above 86.9 ft so no moment capacity needed below this depth

- Insufficient driving resistance due to pile damage, retrofit needed

<table>
<thead>
<tr>
<th>Segmnt Number</th>
<th>Dist. B.G. ft</th>
<th>Impedance kips/ft/s</th>
<th>Imped. Change %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3</td>
<td>410.10</td>
<td>0.00</td>
</tr>
<tr>
<td>26</td>
<td>86.9</td>
<td>410.00</td>
<td>-0.03</td>
</tr>
<tr>
<td>27</td>
<td>90.3</td>
<td>370.00</td>
<td>-9.78</td>
</tr>
<tr>
<td>28</td>
<td>93.6</td>
<td>275.00</td>
<td>-32.94</td>
</tr>
<tr>
<td>29</td>
<td>96.9</td>
<td>150.00</td>
<td>-63.42</td>
</tr>
<tr>
<td>30</td>
<td>100.3</td>
<td>25.00</td>
<td>-93.90</td>
</tr>
<tr>
<td>31</td>
<td>103.6</td>
<td>95.00</td>
<td>-76.84</td>
</tr>
<tr>
<td>32</td>
<td>107.0</td>
<td>175.00</td>
<td>-57.33</td>
</tr>
<tr>
<td>33</td>
<td>110.3</td>
<td>200.00</td>
<td>-51.23</td>
</tr>
<tr>
<td>34</td>
<td>113.7</td>
<td>350.00</td>
<td>-14.66</td>
</tr>
<tr>
<td>35</td>
<td>117.0</td>
<td>410.10</td>
<td>0.00</td>
</tr>
</tbody>
</table>
CYLINDER PILE STRUCTURAL DAMAGE RETROFIT

Top 54” Cylinder Pile El. +17.6 ft

Ground El. +4.7 ft

Top of Cylinder Pile Damage El. -72.9 ft

Bottom of Cylinder Pile Damage El. -82.9 ft

Toe of Cylinder Pile El. -102.9 ft
CYLINDER PILE STRUCTURAL DAMAGE RETROFIT

- Cylinder pile annulus cleaned out

- Rollers used to guide 36” OD x ½” wall thickness open ended steel pipe pile inside cylinder pile

- Steel pile vibrated to below the toe of cylinder pile then impact driven

- Skin friction of cylinder pile above damage point superimposed with end bearing of steel pipe pile to provide adequate driving resistance
QUESTIONS?