Topics

- Pile Properties
- Cylinder and pipe pile details
- Damage potential
- The FHWA Synthesis
- Cylinder pile topics
- Plug formation, a study
- Very large pile example
- Summary

Steel Pile Properties

- Rolled pipe diameters unlimited; spiral welded 10'
- Wall thickness 1" max for spiral weld

Spinning, Post-tensioning

Photos: courtesy Don Theobald, Gulf Coast Prestress

Moving and Installing
Cylinder Pile Properties

- Sizes:
  - US: 36x5, 54x5, 66x6" 
    
    (910x130, 1370x130/150, 1680x150 mm)
  - Other countries: 16, 20, 30"
    
    (400, 500, 750 mm)
  - Concrete strengths:
    - US: 6 to 8 ksi
      
      (42 – 55 MPa)
  - Other countries: same or more

Static Bending Stresses

Driving systems

- Leads which do not sway, bend piles
- Hammer cushion: man made material, uniformly worn
- Helmet: well fitting, evenly striking surface; skirt not to apply horizontal forces
- Pile cushion: plywood stacks, engineered and well assembled

Pile Stabbing

Add-On

Stabbing Guide

Temp. Pile Top
A well designed driving system prevents bending stresses, eccentricities

Photograph: Courtesy Massman Construction

Pile top forces

- Eccentric, misaligned driving forces
- Poorly fitting helmet
- Non-uniformly worn cushion
- Cushion expansion force
- Strand anchoring forces
- Concrete quality problems
- Grout pressure
- Helmet lateral force
- Strain anchoring forces

Problems

Vertical Cracking

Top Damage

Pile top forces

- Non-uniformly worn cushion
- Non-uniform cushion force
- Internal helmet lateral force

Pile top damage due to:

- Uniform driving stresses plus prestress
- Hammer eccentricity and misalignment
- Limited effectiveness of hoop reinforcement
- Complex stress state at pile top

Tensile stress pile damage

- Low ram/pile weight ratios cause for high tension stresses both when driving is easy and when it is very hard
- Additional bending stresses particularly in battered pile driving
- High tension/compression stress cycles cause small tension cracks and eventually damage, particularly under water
Recommendations for damage prevention

- Reduction of allowable driving stresses from 85% to 66% of strength minus prestress
- Monitoring of driving stresses
- Well engineered driving system
- Well aligned hammer - pile to prevent bending
- Careful grouting and prestressing
- High quality concrete and curing

Bending / Local Stress concentrations

... due to
- Hammer Weight
- Pile Batter
- Barge/crane/lead motion

add to
- Driving and pre-stress, post-tensioning stresses
  also
- Non-uniform soil resistance adds to unpredictable additional stresses

Some relevant statements

- Large diameter open ended piles (LDOEPs) are steel or prestressed concrete cylinders 36" or larger in diameter which can provide large axial and lateral resistance even in relatively poor soil conditions
- Load and Resistance Factor Design (LRFD) methods for piles were calibrated using piles with a diameter of 24" or less
- Recent or current projects with LDOEPs San Francisco – Oakland Bay Bridge, Woodrow Wilson Bridge, Tappan Zee Bridge, Kentucky Lakes Bridge, ... in New York which is currently under construction

The Synthesis

Current Practices for Design and Load Testing of Large Diameter Open-End Driven Pipe Piles
Synthesis Results

Results

Synthesis Results

McVay 2004

66" dia OE Cylinder pile
Determined critical g-level of 15 g's for plug slipping

Static: 1962 kips
R-total CAPWAP – restrick with 0 set and no superposition: 1266 kips
(Note: Superposition uses end bearing from EOD and Shaft resistance from BOR)

Synthesis results

Alaska DOT – 12 to 48" dia piles
Developed a design method based on CAPWAP results.

The proposed relationships were used to predict pile resistance on a project with 29 monitored piles driven into silt-rich deltaic deposits.

Dickerson reported “Overall, the agreement between the predictions and the CAPWAP results was good to excellent, and the proposed method provided much more reliable ranges of estimated pile resistance than obtained using widely-adopted, standard of practice procedures.”
Synthesis results

A Comparison of Dynamic and Static Pile Test Results
(OTC, Stevens 2013):

48” dia OEPipe Piles at 40’ and 65’ depth
Uplift Static: 1180 and 2530 kips
R-shaft CAPWAP: 1290 and 2530 kips

78” dia OEPipe Piles at 110’
Uplift Static: 5875 kips
R-shaft CAPWAP: 5930 kips (extrapolated to 53 days using pore water pressure measurements)

Synthesis results: Kentucky Lakes

Table 7: Kentucky Lakes Bridge Test Pile Results

<table>
<thead>
<tr>
<th>Test Pile</th>
<th>EOD CAPWAP Resistance (kips)</th>
<th>72-hour Restrike CAPWAP Resistance (kips)</th>
<th>Estimated Static Resistance (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-1</td>
<td>3300</td>
<td>5000</td>
<td>9550 (Static test)</td>
</tr>
<tr>
<td>K-2</td>
<td>2544</td>
<td>4730</td>
<td>6952 (Static test)</td>
</tr>
<tr>
<td>K-3</td>
<td>2800</td>
<td>5200</td>
<td>8511 (Static test)</td>
</tr>
</tbody>
</table>

Synthesis results: Kentucky Lakes

- For the dynamic records where radiation damping was applied, the model generally resulted in a significantly better signal match quality, indicating the radiation damping allows CAPWAP to better model the signals recorded by the dynamic pile testing equipment.
- The pile resistances calculated with CAPWAP using the radiation damping model also generally produced higher end bearing resistance values than the CAPWAP models without the radiation damping. It appears that the radiation damping model is better suited for estimating the end bearing component of the piles when less pile set is experienced per hammer blow. This is the case when the constrictor plates are engaged on the dense granular soils.
- Wave equation analyses indicated that plugged piles would have high stresses. Additionally there was concern that localized high stresses might be encountered due to the presence of the chert. Testing on the piles typically did not approach as high values as expected.

Synthesis results

Kentucky Lakes, Terracon

48 and 72” dia OEPipe piles with 1 to 2” wall thickness
48” plug models after Paikowsky

To monitor the formation of a plug in the interior of the pile, a simple device called a pile plug monitoring device (PPMD) was constructed. The PPMD consisted of lead weights attached to a 100 foot fiberglass measuring tape. The weights would fall to the top of the soil column inside of the piles, allowing the distance from the top to the soil to be computed. Access to the interior of the pile was made through a vent hole near the top of the pile. The PPMDs were read intermittently throughout test pile installation. The data showed that soil was rising inside both piles during driving, indicating that disturbed soil and water was accumulating in the pile rather than a pile plug forming and traveling down with the pile.
Synthesis results
US 378 Bridge over Pee Dee River (South Carolina) S&ME

Longitudinal cracks
Potential causes:
• Poisson’s effect and/or insufficient hoop reinforcement
  – (may not be a problem)
• complex stress state at pile top or pile bottom
• concrete and/or manufacturing defects
  – internal hydrostatic water pressure
  – (provide water escape hole)
• internal excess soil or pore water pressure
  – (wash out plug, bail out water!)
• internal dynamic air/water pressure

CANNOT BE DETECTED BY PDA

Dynamic Considerations: Plug inertia vs internal resistance
Assuming a plug length equal to 1, 3 and 5 diameter pile diameters
Assuming 100 g’s steel acceleration
The graph shows internal friction and inertia (no end bearing)

Conclusion: under these VERY simplified circumstances a plug will slip if the diameter is more than ~40 inches

Unplugged pile toe acceleration
Concrete cylinder pile

---

Notes:
- Fig 34: Summary of Measurements and US 378 Bridge
- Dynamic Plugging?
- Static Plugging
- Unplugged pile toe acceleration
Loss of Resistance Due to Pile Driving

- Sand porewater pressure changes
- Liquefaction
- Clay remolding, thixotrophy
- Other?
- Arching in granular soils
  - not during driving at toe: reduced end bearing
  - During driving at shaft: reduced friction

Friction Fatigue: Loss of resistance

Friction fatigue considers that the SRD is equal to the LTSR at the pile toe and decreases exponentially above the toe (loss depends on the distance from the toe).

Loss of friction due to pile lateral motions

Loss of friction due to arching
Friction Fatigue: Loss of resistance

- Friction fatigue considers that the SRD is equal to the LTSR at the pile toe and decreases exponentially above the toe distance from the toe.
- In contrast, the standard GRLWEAP approach assumes full loss of resistance in a particular soil layer.

GRLWEAP Friction Fatigue Approach

- Resistance Ratio, \( f_r = \frac{R_{SRD}}{R_{LTSR}} \)
- Degradation distance, \( L_{lim} \) (Limit Length, 20 to 150 m)
- Undegraded distance, \( f_0 \) (say 0.05)
- Exponent for degradation shape, \( f_1 \) (say 0.001)

\[ R_{SRD} = R_{LTSR} \left( 1 - f_0 \right) \left( 1 - f_1 L_{toe} \right)^{-1 / f_1} \]

Plug modeling

- In Preparation of an improved GRLWEAP/CAPWAP model let us consider what we must calculate:
- Displacement of steel and plug
- Velocity of steel and plug

Unknowns to be determined:

- Steel friction, \( f_{ste} \)
- Plug friction, \( f_{pl} \)
- Unknowns to be determined: \( f_{ste}, q_{ste}, f_{pl}, q_{pl} \)

Simplified model: single plug mass

- Unknowns to be determined: \( f_{ste}, q_{ste}, f_{pl}, q_{pl} \) Plus damping

Pipe pile:

- Steel only
- Plug with full end bearing

Pipe pile:

- Steel only
- Plug with full end bearing
Example 18 inch pile

**INPUT - Easy driving record**

Pile is rigidly linked to plug – displacements are the same.

**Example 18 inch pile**

**INPUT - Hard driving record**

Plug is linked to steel pipe with an elasto-plastic spring (R-int, q-int)

**Example 18 inch pile**

**INPUT - Easy driving record**

Plug is linked to steel pipe with an elasto-plastic spring (R-int, q-int)

**Example 18 inch pile**

**INPUT - Hard driving record**

Plug is linked to steel pipe with an elasto-plastic spring (R-int, q-int)

**Conclusion from simplified plug model**

- The study clearly shows that the full activation of the toe resistance against the plug is as important as plug slippage when attempting to mobilize and calculate full resistance
- The model has to consider
  - the internal friction on plug and pile
  - the plug compressibility and mass
  - different quakes and unit resistance values for annulus when not plugging and unit toe resistance for plugged analysis
A Word about Very Large Pipes and Vibratory Analysis
21m dia Steel; APE Octagon; Photo Galerie

GRLWEAP Calculated of Rate of Penetration

Yangtze Caisson:
12x0.25 m concrete pipe, 25 m long
4 APE 4B hammers (683 kg m, 20 Hz, 3000 kW); 8 clamps + beams
Clay, silty Sand; N at most 3
Shaft resistance (inside and out) 10 kPa
   Analyzed at 80% and 100%
Toe resistance 90 kPa

Thank You
Discussion?