PDA Testing Objectives:

**Economical Load Testing**

- Dynamic Testing
- Static Testing

*Outline*

- Methods
  - Stresses
  - Integrity
  - Capacity
  - Energy
- Examples
- Summary

**PDA Testing Objectives:**

Results for every hammer blow

- Stresses
  - At location of sensors
  - Maximum tension stress
  - Pile toe stresses
  - Pile Integrity (impedance change)
- Soil Resistance
  - At the time of testing (EOD or BOR)
  - Shaft resistance estimate
- Hammer Performance
  - Energy transferred to pile
  - Stroke of diesel hammers

**Dynamic Pile Testing Approach**

- Basically we have to measure Pile Top Force and Pile Top Velocity.
- Then we have to process the data with the Pile Driving Analyzer® System (PDA)

**Measuring Strain and Acceleration**

(need to do it on opposite pile sides)

- Strain transducer
- Accelerometer
PDA testing data acquisition

- Need Minimum 2 strain measurements per pile to compensate for bending

Mounting the sensors

Alternative force transducer or \( F=ma \)

For \( F=ma \) or top load cell testing, accelerometers must be attached to pile top.

Strain and Acceleration Sensors

Wireless

Under Water

Sensor Installation/Protection

H-piles

Pipe piles

Lofting a test pile
Smart and Wireless Sensors
Make for Happy Testers

SiteLink and Wireless Testing
Makes also for happy contractors and clients

SiteLink Advantages

- No traveling/scheduling cost/delays/issues
- Immediate analysis and quick report submittal
- Increased efficiency of test engineer
- Remote supervision of inexperienced personnel avoids errors

Basic Strain and Acceleration Measurements

$\epsilon_1(t), \epsilon_2(t)$, one strain on each side

$a_1(t), a_2(t)$, one acc. on each side

Standard Presentation

$$F = \frac{1}{2} (S_1 + S_2) (EM \times AR)$$

$$v = \frac{1}{2} \int (a_1 + a_2) \, dt$$

$$F_u = \frac{1}{2} (F - vZ)$$

$$F_d = \frac{1}{2} (F + vZ)$$
Maximum Force, FMX

Compresive Stress Results
At Gage Location (CSX and CSI) and at Bottom (CSB)

- CSX = 233 MPa (33.8 ksi)
- CSI = 245 MPa (35.5 ksi)

Calculated at Bottom: CSB = 264 MPa (38.2 ksi)

Calculating Tension Stresses Below Pile Top
From Force in Wave-down and Wave-up

Wave Superposition for Force Below Sensors

Tension Stress Calculation (Wave-Up)

Tension Stress Maximum and Distribution
Another Tension Stress Example

Pile Damage: BTA, LTD

A pile impedance reduction (damage?) causes a tension reflection before 2L/c.

The time at which the tension reflection arrives at the gage location indicates the depth to the damage: LTD = \left(\frac{t_{\text{damage}}}{2}\right) c

β - Formula Derivation

\begin{align*}
\beta &= \frac{Z_2}{Z_1}:
\frac{(- F_{u,1} + F_{d,1})}{(F_{u,1} + F_{d,1})} = F_{d,2} = F_{u,1} + F_{d,1}
\end{align*}

\beta = \frac{(F_{u,1} + F_{d,1})}{(- F_{u,1} + F_{d,1})}

Damage Assessment Example

\begin{align*}
F_{d,1} &= \frac{1}{4}(F_{u,1} + Zv_{t,1}) \\
F_{u,1} &= \frac{1}{4}(F_{u,1} - Zv_{t,1})
\end{align*}

Toe Damage Detection: Early Record

BN 220

24 inch PSC  L = 56 ft  WS 14,000 ft/sec

Damage Detection: Spliced pile Example

Good Pile  Bad Pile: Early reflection
Resistance Waves

Upward traveling wave at time 2L/c:

\[ F_{u,2} = -F_{d,1} + \frac{1}{2} R_i + \frac{1}{2} R_i + R_B \]

RTL = \( F_{u,2} + F_{d,1} \)

The Static Resistance is Total Resistance - Damping

\[ R_s = RTL - R_D \]

Assuming \( R_D = J_v v \) (\( \text{N/m/s/m/s} \))

**Introducing:** \( J_c = J_v / Z \) ..... Case Damping Factor

Then \( R_D = J_c Z v \)

Using pile toe velocity as representative

\[ v_{toe} = 2 F_{d,1} - RTL \]

\[ R_{static} = RTL - J_c (2 F_{d,1} - RTL) \]

\[ v_{toe} \]

\[ R_{static} = (1 - J_c) F_{d,1} + (1 + J_c) F_{u,2} \]
\[ R_{\text{static}} = (1 - J_c) F_{d,1} + (1 + J_c) F_{u,2} \]

Time of \( F_{d,1} \) and \( F_{u,2} \)

We calculate \( R_{\text{static}} \) at the time when it gives the maximum activated (mobilized) resistance value.

Pile with shaft resistance:

Equilibrium and Continuity

Compressive upward wave

\[ F_u = \frac{1}{2} R; \quad v_u = -\frac{1}{2} R/Z \]

Tensile downward wave

\[ F_d = -\frac{1}{2} R; \quad v_d = -\frac{1}{2} R/Z \]

Shaft and Toe Resistance

Friction Pile Records

Wave-up Force Change Due to Friction
Calculating the Transferred Energy

\[ \text{Max } E_T = \int F(t) v(t) \, dt \]

\[ \eta_T = \frac{\text{ENTHRU}}{E_R} \]

\[ E_R = \frac{W_T}{h} \]

Manufacturer's Rating

Measure

Force, \( F(t) \)

Velocity, \( v(t) \)

Statistical Summaries for SA–Air/Steam Hammers

Transfer Ratios at End of Driving

- **Steel Piles:** \( N=747 \)
  - Mean 87%
  - Mean 41%

- **Concrete Piles:** \( N=194 \)
Statistical summaries for Diesel Hammers

Transfer ratios at End of Driving

<table>
<thead>
<tr>
<th>Hammer Performance</th>
<th>Steel Piles; N=1419</th>
<th>Concrete Piles; N=668</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>39%</td>
<td>Mean</td>
</tr>
</tbody>
</table>

Statistical summaries for Hydraulic Hammers

Transfer ratios at End of Driving

<table>
<thead>
<tr>
<th>Hammer Performance</th>
<th>Steel Piles; N=203</th>
<th>Concrete Piles; N=67</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>69%</td>
<td>Mean</td>
</tr>
</tbody>
</table>

Frequency of transfer ratios for

SA Air/Steam, Diesel

DA Air/Steam, Hydraulic

Transfer Ratio

Hammer Energy Variations

Same Hammer, Same Site at EOD for 42 Piles

- Hammer was a D19-42 OE diesel
- Steel H-piles; EOD
- Claystone bearing layer
- Hammer energy appeared not related to driving resistance

Rausche et al., 2006. Mastering the art of dynamic pile testing, SWC Kuala Lumpur

A Monitoring Example: Rigolet Bridge

Cylinder Piles 66” dia.
PDA Measurements

including circumferential strain measurements!

Cylinder Pile Data (EOD)

Example: 914 mm (36") dia. Jacket leg pile

Length: 92 m
Required Penetration: 70 m
Hammer: Vulcan 530 (13.5 Mg x 1.5 m)
Concern: Damage due to Calcarenite Layer

Example: Soil Description

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>To</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Loose carbonate silty SAND</td>
</tr>
<tr>
<td>18</td>
<td>Medium dense carbonate sandy SILT</td>
</tr>
<tr>
<td>22</td>
<td>Medium dense carbonate very silty fine to medium SAND</td>
</tr>
<tr>
<td>36</td>
<td>Firm carbonate clayey SILT</td>
</tr>
<tr>
<td>46</td>
<td>Weak to moderately strong CALCARENITE</td>
</tr>
<tr>
<td>80</td>
<td>Stiff to very stiff CLAY</td>
</tr>
</tbody>
</table>

PDA Display: prior to hard driving (39.0 m)
PDA Display: Highest Driving Resistance (39.3 m)

Installation blow counts and stresses

Installation blow counts and stresses

A 24” Square PSC Pile Example

A Concrete Pile: Wave equation + Testing

GRLWEAP Static Soil Analysis

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description</th>
<th>N</th>
<th>qu, kPa (ksf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (13)</td>
<td>Sand</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8 (26)</td>
<td>Sand</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>13.4 (44)</td>
<td>Clay</td>
<td>180</td>
<td>(3.8)</td>
</tr>
<tr>
<td>22 (72)</td>
<td>Clay with Sand Lenses</td>
<td>300</td>
<td>(6.2)</td>
</tr>
</tbody>
</table>

Water Table at 3 m or 10’ depth

| qh | 1700 kN
| Rshft | 1200 kN
Wave Equation analysis: Bearing Graph

At refusal (1210 Bl/m or 370 Bl/ft) we would expect 4000 kN capacity at a stroke of 2.5 m and a transferred energy of 26.8 kJ.

Summary of Capacities Based on EOD

Check whether additional capacity can be gained with time by doing a restrike test. Pile is driven 6 inches after 24 hours waiting time. Blow Count now is 300 Bl/m (90 bl/ft)

Hammer Performance Results

End of Drive (445 Bl/ft)

Beginning of 24 hr Restrike (90 Bl/ft)

Capacity Summary Based on EOD and BOR

Capacity and (LRFD) Safe Load Summary

PDA Results and Comparison GRLWEAP

Transfer Ratio(%) 21 27 (Refusal) 29

Stroke in m 8.8 8.3 11.3

Transfer Ratio(%) 35 26 (90 bpf) N/A

Stroke in ft 10.7 8.3 11.3

Transfer Ratio(%) 35 26 (90 bpf) N/A

Check whether additional capacity can be gained with time by doing a restrike test. Pile is driven 6 inches after 24 hours waiting time. Blow Count now is 300 Bl/m (90 bl/ft)

Capacity and (LRFD) Safe Load Summary

PDA Results and Comparison GRLWEAP
Taking Advantage of Soil Setup

Nominal or Required Capacity is $R_{REQ}$ (say 400 tons)
Determine End of Drive Capacity from Monitoring, $R_{EOD}$ (say 450 tons)
Find out Restrike Capacity, $R_{BOR}$ (say 550 tons)
Setup Factor is $f_{SETUP} = \frac{R_{BOR}}{R_{EOD}}$ (550/450 = 1.22)
Drive Pile at EOD to $f_{SETUP} \times R_{REQ}$ (400/1.22 = 328 tons)

Demonstrate Adequacy by Restrike Testing

Soil Setup

St. Johns River Bridge:
Increased loads by 33% with substantially shorter piles (set-up considered)
Total project cost:
- $130 million (estimate)
- $110 million (actual)
- $20 million (savings)

Scales & Wescott, FDOT, presentation at PDCA Roundtable Orlando 2004

Summary

- The PDA processes pile top force and velocity records according to the (closed form solution) Case Method; results allow for assessment of
  - Pile Stresses
  - Hammer Performance
  - Soil Resistance
  - Pile Integrity
- These results are displayed in Real Time and, therefore, allow for real time monitoring of the pile installation
- For Dynamic load testing Restrikes + CAPWAP are usually necessary
- After PDA+CAPWAP the GRLWEAP analysis can be refined

Thank you for your attention
For further information see: www.pile.com
QUESTIONS?

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