Dynamic Monitoring of Piles

Ryan L. Eaves, P.E.
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<table>
<thead>
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<th></th>
<th>Title</th>
<th>Pages</th>
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</thead>
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<td>4</td>
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<td>35-40</td>
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</table>
Piling Basics

- Piling are most often used along the Gulf Coast or in East Texas.
- Piling are well suited for softer soils, but not for hard soils or rock.
- Piling typically gain most of their load capacity from skin friction.
Pile Driving Review

- A pile is a prefabricated element, made of concrete, steel, or timber. It is generally long and slender.
- A pile is installed by hammering it into the ground using a pile driving hammer.
- Piling can be designed to support modest compressive and lateral loads. They generally cannot support as much load as a drilled shaft, so are often grouped under footings when heavy loads need to be supported.

<table>
<thead>
<tr>
<th>Size</th>
<th>Maximum Length</th>
<th>Abutments and Trestle Bents</th>
<th>Footings (per Pile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 in.</td>
<td>85 ft.</td>
<td>75 ton</td>
<td>125 tons</td>
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<tr>
<td>18 in.</td>
<td>95 ft.</td>
<td>90 tons</td>
<td>175 tons</td>
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<tr>
<td>20 in.</td>
<td>105 ft.</td>
<td>110 tons</td>
<td>225 tons</td>
</tr>
<tr>
<td>24 in.</td>
<td>125 ft.</td>
<td>140 tons</td>
<td>300 tons</td>
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</table>
Pile Driving System

- **Leads** – Used to hold piling and hammer, and keep them aligned with each other.
- **Power Hammer** – Uses air pressure or diesel to lift and drop heavy ram.
- **Helmet** – Connects the hammer to the top of the pile.
- **Cushion(s)** – Absorb some energy to prevent damage to pile and hammer.
Pile Driving System

Impact Block
Striker Plate
Hammer Cushion
Helmet
Pile Cushion
Pile
Specifications

- Item 404 – Driving Piling
- Item 405 – Foundation Load Test
  - 405-6002 Foundation Load Test (D4945) (Pile)
  - 405-6003 Foundation Load Test (D4945) (Drilled Shaft)
- Other Relevant Items
  - Item 406 - Timber Piling
  - Item 407 – Steel Piling
  - Item 409 – Prestressed Concrete Piling
Cracked Piling

- Most common cause is **soft** soil!!
- Striking a concrete pile a full blow with a heavy hammer requires that the pile have good resistance at the tip.
- If not, result is high tensile stress and horizontal cracking of the pile.
- May require use of smaller hammer or lower fuel setting (shorter drop height)
Hard Driving

- As piling is being driven, driving becomes very difficult well above plan grade.
- Can occur for several reasons;
  - Pile hammer is too small.
  - Pile is too long.
  - Soil has a hard layer near the surface.
  - Soil is too hard overall for advancement of pilling

Concrete Piling damaged by hard driving condition.
Pile Driving Issues

- Pile driving system approval.
- Driving system be sized appropriately based on pile type, weight, and required resistance.
- Item 404 “Driving Pilling”, Table 1 provides reasonable guidelines for sizing hammers based in pile weight and required resistance.
- Requirements of Table 1 work well for “typical” soils and pile loads.
- Particularly hard or soft soil driving conditions may require an additional check.
### Pile Driving System

#### Table 1

<table>
<thead>
<tr>
<th>Piling Type</th>
<th>Hammer Type</th>
<th>Ram Weight (lb.)</th>
<th>Maximum Ram Stroke (ft.)</th>
<th>Minimum Hammer Energy (ft.-lb.)</th>
</tr>
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<tbody>
<tr>
<td>Timber</td>
<td>Air, Hydraulic</td>
<td>2,000 min.</td>
<td>5</td>
<td>330R</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2,000 min.</td>
<td>10</td>
<td>330R</td>
</tr>
<tr>
<td>Steel</td>
<td>Air, Hydraulic</td>
<td>3,000 min.</td>
<td>5</td>
<td>Larger of 250R or 2-1/2 Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2,000 min.</td>
<td>10</td>
<td>Larger of 250R or 2-1/2 Wp</td>
</tr>
<tr>
<td>Concrete</td>
<td>Air, Hydraulic</td>
<td>3,000 min., but not less than 1/4 Wp</td>
<td>5</td>
<td>250R, but not less than 1 ft.-lb. per lb. of pile weight</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2,700 min., but not less than 1/4 Wp</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

1. R = Design load in tons. Wp = Weight of pile in pounds based on plan length.
2. Diesel hammers with less ram weight or greater ram stroke are permitted if a wave equation analysis indicates that the combination of ram weight, stroke, and cushioning will not overstress the piling.
Pile Driving System

- Large, heavily loaded piling require large hammers to achieve necessary embedment.
- Large hammers can create high compressive stresses during hard driving.
- Large hammers can create high tensile stresses during easy driving.
- More sophisticated evaluation of the pile driving system should be considered when:
  - Driving piling in hard material is expected
  - Driving heavy piling in potentially soft material
  - Proposed pile driving system does not satisfy ram stroke requirements of Item 404 Table 1
Evaluating Pile Driving System

- Perform wave equation analysis to model driving system and predict tensile loads in the piling.
- Use the program to evaluate changes to hammer stroke, cushion thickness and material, etc.
- Field instrumentation may also be used to directly measure acceleration and stresses during pile driving.

Dynamic Testing Methods
Wave Equation Analysis

- Computer analysis that looks at the specifics of the driving system, soil profile, etc. and predicts the stresses in the pile during driving.
- Requires additional information about the hammer cushion, helmet, specific hammer model, pile cushion, etc.

```
THE CONTRACTOR SHALL SUBMIT THE WAVE EQUATION ANALYSES OF THE PROPOSED PILE DRIVING SYSTEM USING GRLWEAP SOFTWARE OR EQUIVALENT. THE CONTRACTOR SHALL DEMONSTRATE THROUGH ANALYSIS THAT THE PILING CAN BE DRIVEN SAFELY TO THEIR REQUIRED TIP ELEVATION WITHOUT EXCESSIVE TENSILE OR COMPRRESSIVE DRIVING STRESS IN THE PILING. PILE DRIVING SHALLNOT PROCEED UNTIL THE CONTRACTOR HAS RECEIVED APPROVAL OF THE PROPOSED SYSTEM.
```
Contractor submitted analysis
Wave Equation Analysis

- Instruct the contractor to get a larger (or smaller) hammer.
- Paragraph 404.2 and Note 2 under Table 1 allows hammers that don’t meet the ram stroke requirements if a “Wave Equation Analysis” is performed indicating that the procedure will work.
- Engineer may also call for a Wave Equation Analysis if there is particularly soft or hard soils anticipated.
Pile Resistance

- Driving Formula (Item 404)
- Single-acting Power Hammers:
  - \( P = \frac{2 \times W \times H}{(s + 0.1)} \)
  - \( P = \text{Calculated Resistance (lbs.) (Allowable)} \)
  - \( W = \text{Weight of Ram (lbs.)} \)
  - \( H = \text{Height of Ram Fall (ft.)} \)
  - \( s = \text{Average Penetration for last 20 blows (inches per blow)} \)
- Compare with Foundation Load (Built-in SF into Driving Formula)

### GENERAL NOTES:

Designed according to AASHTO LRFD Bridge Specifications, 5th Edition (2010).
Class "C" concrete strength shall be \( f'c = 3,600 \text{ psi} \).
All Cap reinforcing shall be Grade 60.
See Footing Detail Sheet and Foundation Detail Standard Sheet, FD(MOD), for foundation details and notes.

Calculated Foundation Loads ~
Bents 2-8 = 70 Tons / Pile
Testing Types

- Static
- Dynamic
  - Pile Foundation Load Test
  - Drilled Shaft Foundation Load Test
Dynamic Testing

- Alternative to Static Load tests
  - Less Expensive
  - Less Time Consuming
High Strain Dynamic Testing

- Dynamic Testing (Driven Pile)
- Dynamic Testing (Drilled Shaft)

- Governed by ASTM D4945
  - Concepts and procedures applies to both Driven Piles and Drilled Shafts
  - Acquired data can be analyzed to evaluate
    - The performance of the driving system
    - The integrity of the pile
    - The maximum compressive and tensile stresses occurring in the pile
      (Source: ASTM International)
Dynamic Testing for Driven Piles

- More accurate capacity estimation than the hammer formula

<table>
<thead>
<tr>
<th>Bent#</th>
<th>Pile Type</th>
<th>Bent Type</th>
<th>Min. Lateral Ele. (FT)</th>
<th>Plan Tip. (FT)</th>
<th>Design governed by</th>
<th>Foundation Load (Ton)</th>
<th>Foundation Load (kips)</th>
<th>Ultimate Capacity Required (kips)</th>
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</thead>
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<tr>
<td>Bent2</td>
<td>24&quot; SQ</td>
<td>Trestle</td>
<td>-114</td>
<td></td>
<td>Axial</td>
<td>145</td>
<td>290</td>
<td>580</td>
</tr>
<tr>
<td>Bent6</td>
<td>24&quot; SQ</td>
<td>Trestle</td>
<td>-109</td>
<td></td>
<td>Axial</td>
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<td>290</td>
<td>580</td>
</tr>
<tr>
<td>Bent9</td>
<td>24&quot; SQ</td>
<td>Trestle</td>
<td>-53</td>
<td></td>
<td>Axial</td>
<td>145</td>
<td>290</td>
<td>580</td>
</tr>
<tr>
<td>Bent11</td>
<td>54&quot; CYL.</td>
<td>Trestle</td>
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<td>-64</td>
<td>Lateral</td>
<td>306</td>
<td>612</td>
<td>1224</td>
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<tr>
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<td>Trestle</td>
<td>-64</td>
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<td>306</td>
<td>612</td>
<td>1224</td>
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<tr>
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<td>-120</td>
<td>-135</td>
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<td>864</td>
<td>1728</td>
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<td>Footing</td>
<td>-125</td>
<td>-125</td>
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<td>432</td>
<td>864</td>
<td>1728</td>
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</tbody>
</table>
Dynamic Testing Benefits

- Lower cost and time than static test methods
- Can test any pile type
- Can test while pile is being driven to plan tip elevation

Data Provided (for each blow):
  - Pile Integrity: determine if piles are damaged during driving
  - Estimate pile driving impact stresses
  - Performance of the pile driving system
  - Pile Capacity
Dynamic Testing System

- Strain Gauge and Accelerometer
  - Able to determine force and wave velocity

Source: FHWA
### Example Dynamic Load Testing Result

<table>
<thead>
<tr>
<th>Bent#</th>
<th>Pile Type</th>
<th>Plan Tip. (FT)</th>
<th>Ultimate Capacity Required (kips)</th>
<th>CAPWAP (EOD) Ele. Tested (FT)</th>
<th>Total (kips)</th>
<th>CAPWAP (BOR) Ele. Tested (FT)</th>
<th>(Hrs)</th>
<th>Total (kips)</th>
<th>K factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bent2</td>
<td>24&quot; SQ</td>
<td>-114</td>
<td>580</td>
<td>-69.4</td>
<td>459</td>
<td>-69.6</td>
<td>3</td>
<td>590</td>
<td>1.29</td>
</tr>
<tr>
<td>Bent6</td>
<td>24&quot; SQ</td>
<td>-109</td>
<td>580</td>
<td>-89.3</td>
<td>411</td>
<td>-89.3</td>
<td>116</td>
<td>768</td>
<td>1.87</td>
</tr>
<tr>
<td>Bent9</td>
<td>24&quot; SQ</td>
<td>-53</td>
<td>580</td>
<td>-49.7</td>
<td>645</td>
<td>-49.73</td>
<td>148</td>
<td>663</td>
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<td>24</td>
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<td>2120</td>
<td>2.91</td>
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<td>1070</td>
<td>-125.1</td>
<td>185.5</td>
<td>2400</td>
<td>2.24</td>
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</tbody>
</table>
Determine Dynamic Resistance

- If driving resistance is low, we often let the pile “rest” anywhere from a few hours to 7 days. This allows disturbed soil around the pile to ‘set-up’. When we get back on to the piling, the resistance often increases 50 - 200%.
- Common practice is to stop driving the pile a foot or two above grade, then wait.
- Waiting time can vary from a few hours to 7 days. Overnight is most common.
- Begin driving the pile again after allowing the soil to “set up”.
Pile Set-Up

- Some soils will begin to remold and lose strength after just a few inches of driving.
- The “best” indicator of true pile capacity is in the first inch or so of a re-drive.
- Waiting to measure set until the end of the re-drive may put you right back where you started.
## Example Dynamic Load Testing Result

<table>
<thead>
<tr>
<th>Bent#</th>
<th>Pile Type</th>
<th>Plan Tip. (FT)</th>
<th>Ultimate Capacity Required (kips)</th>
<th>CAPWAP (EOD) Ele. Tested (FT)</th>
<th>Total (kips)</th>
<th>CAPWAP (BOR) Ele. Tested (FT)</th>
<th>(Hrs)</th>
<th>Total (kips)</th>
<th>K factor</th>
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<tr>
<td>Bent2</td>
<td>24&quot; SQ</td>
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<td>580</td>
<td>-69.4</td>
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<td>-69.6</td>
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<td>590</td>
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</tr>
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<td>-49.7</td>
<td>645</td>
<td>-49.7</td>
<td>148</td>
<td>663</td>
<td>1.03</td>
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<td>-125.1</td>
<td>185.5</td>
<td>2400</td>
<td>2.24</td>
</tr>
</tbody>
</table>
K Factor

Set-up Factor (Total Capacity)

![Graph showing Set-up Factor (Total Capacity)]
Example Project

- 24” and 36” Cylindrical Steel Pipe Piles
- Wave Equation Analysis Required
- 21 Dynamic Load tests on 7 Piles
  - Measured Capacity at
    - End of Driving
    - 1-Day Beginning of Restrike
    - 7-Day Beginning of Restrike
- Test Piles to be completed prior to production piles
Wave Equation Analyses Notes

- “Submit the Wave Equation Analyses of the proposed pile driving system using GRLWEAP software or equivalent with an electronic input file. Demonstrate that the piling can be driven safely to their required tip elevation without excessive driving stress in the piling through analysis.”

- “The ultimate pile capacity is two times of the foundation load shown in the table.”

- “Pile driving shall not proceed until the contractor has received approval of the proposed system. The wave equation analyses is not paid for directly but will be considered subsidiary to “Steel Pipe Piling” item.”
“This work consists of obtaining dynamic measurements with the Pile Driving Analyzer (PDA) of monitor production piles during initial pile driving and during pile restrikes at times shown in the table. Dynamic monitoring will be conducted on the first production pile in each bent specified in Table of High Strain Dynamic Testing.”

“Pile restrikes for monitor piling may be performed in accordance with the time intervals specified below. Monitor piling with dynamic monitoring shall have 1-day and 7-days restrike after the initial pile installation with the Pile Driving Analyzer. The engineer may require additional pile restrike.”

“The Contractor shall secure the Dynamic Testing Consultant (DTC) to perform Case Pile Wave Analysis Program (CAPWAP) analysis for each occurrence of dynamic monitoring. “
# PDA Test Results

<table>
<thead>
<tr>
<th>Bent No</th>
<th>Pile Size in</th>
<th>1st Phase Test Type</th>
<th>Penetration Depth ft</th>
<th>Plan Length ft</th>
<th>CAPWAP Load kips</th>
<th>FDN Load ton</th>
<th>Ult. Load kips</th>
<th>K factor</th>
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</thead>
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<td></td>
<td></td>
<td>1day BOR</td>
<td>104</td>
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<td></td>
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<td>112</td>
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<td>660</td>
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<tr>
<td></td>
<td></td>
<td>1day BOR</td>
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<td>112</td>
<td>630</td>
<td>165</td>
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<td>112</td>
<td>975</td>
<td>165</td>
<td>660</td>
<td>2.4</td>
</tr>
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<td>36</td>
<td>EOD</td>
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<td>207</td>
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Results

- Use to verify pile elevation and verify stresses predicted in GRLWEAP analysis
  - Checked pile driving system and contractor’s installation plan
  - Verified that piles reached desired design capacity
  - Allowed for optimization of Pile Lengths
Drilled Shaft Load Testing

- Uses same concept and equipment as PDA testing method for Piling
  - Drop hammer apparatus on installed drilled shaft
  - Drop Weight is 2%-5% of target ultimate capacity
  - Able to provide shaft integrity information as well as predicted capacity
In Conjunction with TIP testing

- Drilled shaft with Tie-Beams installed to underpin existing truss bridge
- 2 drilled shaft load tests were performed on production drilled shafts on two bents after TIP testing showed issues
Plan Notes

- Relevant Plan Notes and how to implement

**Thermal Integrity Profiler (TIP) Testing of Drilled Shaft (SS 4021):** Perform the nondestructive testing (NDT) method termed TIP testing to check the integrity of designated production drilled shafts as shown in the table below. Coordinate testing with the Engineer a minimum of one week prior to the desired testing date. The Engineer will choose the drilled shafts to be tested.

**High Strain Dynamic Testing of Drilled Shaft (Item 405 – Foundation Load Test):** High Strain Dynamic Testing may be performed on any production drilled shaft suspected to be a deficient drilled shaft based on TIP testing result and/or shaft installation record. Furnish all materials, equipment, and labor necessary to conduct the high strain dynamic testing of drilled shaft. Coordinate testing with the Engineer a minimum of one week prior to the desired testing date. TxDOT personnel will be present during testing.
Test Results

- Nearly 2x ultimate capacity and minimal movement

Bent 17

Bent 27
Results

- Able to verify in place capacity exceeded ultimate capacity
Conclusion

- Dynamic testing methods provide an accurate and non-destructive capacity estimate on production foundation elements
- Much faster and less expensive than static testing methods with comparable results
- Enables more economic pile length design
- Higher confidence level in pile capacity
- More accurate evaluation of pile set up in given soil
Questions?

- For further questions or assistance contact
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