Static Testing

- Expensive
- Time consuming
Dynamic Pile Testing with the Pile Driving Analyzer®

Quality Assurance for Deep Foundations

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DYNAMIC TESTING

- Research began at Case Institute of Technology (Cleveland) in 1964 under G. Goble
- Developed “Case Method” – “PDA”
  - Pile capacity from pile top measurements
- WEAP (Wave Equation Analysis Program)
- CAPWAP (CAse Pile Wave Analysis Program)
DYNAMIC METHODS

• Do not hinder pile driving
• Are much less expensive than static tests
• Can test many piles (a representative sample)
Case Method – PDA

• CONSTRUCTION CONTROL
  – Test sample of production piles to insure capacity over entire project.

• DESIGN
  – Can be cost effective to test for pile capacity as a function of penetration
    • Lower penetration to reach design capacity.

• REPLACE OR SUPPLEMENT STATIC TESTS
  – For large capacity piles
  – Offshore environments
Case Method – PDA

• RESULTS
  – Hammer performance
    • Compute transferred energy, efficiency
    • Monitor effects of changes in hammer cushion, helmet and pile cushion
  – Pile stresses
    • Compressive (hard driving)
    • Tensile (easy driving)
  – Pile integrity
  – Pile capacity
GRLWEAP

**INPUT**
- Hammer properties
- Hammer and pile cushion properties
- Helmet weight
- Pile Properties
- Soil Properties
  - Quakes, damping, resistance distribution

**OUTPUT**
- Resistance vs. blow count
- Stresses vs. pile length/blow count
- Transferred hammer energy
CAPWAP

PROCEDURE:
1. Input soil model (quakes, damping, etc.)
2. Use measured velocity as input
3. Compute pile top force
4. Compare computed force to measured force
5. Modify soil model as necessary until field and measured force are in agreement
CAPWAP

• OUTPUT:
  1. Ultimate capacity and distribution
  2. Stresses vs. pile length
  3. Quakes
  4. Damping factors

Used to refine GRLWEAP
Dynamic Testing Benefits

• More information in less time (reduces delays):
  • Confirms pile capacity design
  • Evaluates integrity, stresses, hammer energy

• Improves quality control
  • (test more piles; tests “problem piles”)

• Rational means to reduce pile costs
  • shorter piles or fewer piles (lower S.F.)

• Significantly less cost than static test
Case Method

1958: first thesis
1964: field testing began under direction of Dr. G.G. Goble

Compute from measurements
- hammer performance
- driving stresses
- pile integrity
- capacity

“Monitoring”
“Dynamic Load testing”
**Dynamic Pile Testing**

- Load is applied by impacting ram
- Load is measured by strain transducers
- Motion is measured by accelerometers
Holes are prepared for 1/4-20 or 6 mm bolts. For concrete piles use a “drill template” to hold spacing and install concrete anchors.
“PDA”

Pile Driving Analyzer®
Hammer Performance

Energy = $\int Fv \, (dt)$

Why is it important?

- Contractor productivity
- Sufficient for pile installation to design depth and/or to required capacity
Efficiency = \( \frac{E_m}{E_r} \)

- \( E_m \): Measured Transf. Energy
- \( E_r \): Rated Energy

Efficiencies on concrete piles are lower ~ 10%
Hammer performance and cushion evaluation
Driving Stresses

Knowing stresses leads to steps to reduce risk of pile damage due to:

- **Compression stress**
  - at both Top and Bottom
- **Tension stress** (concrete piles)
- **Bending, Alignment**
Average force is proportional and reasonable; 2 sensors can compensate large bending.
USA - AASHTO

**Steel piles**
- Compression: 90% of yield strength for steel

**Concrete piles**
- Compression: 85% of c.strength - prestress
- Tension (PS): prestress + (50% of t.strength)
- Compression: 85% of c.strength
- Tension (RR): 70% of yield of reinforcement
Pile integrity

Problem: Broken piles have low capacity

Detect damage by:

- blow count record, or very long piles
- visually (above ground, closed pipes)
- extraction
- Electronically (PDA or PIT)
- or static load test
Integrity

- Magnitude of damage
- Location
Integrity by PDA dynamic testing

- Normal time return (pile length OK)
- Small damage
- Early return indicates shorter pile length
- Large damage

1
2
3
4

blow

Integrity by PDA dynamic testing

- Normal time return (pile length OK)
- Small damage
- Early return indicates shorter pile length
- Large damage

blow
Small damage

Large damage

New toe
pile shorter
Pile failed at pickup point. Due to early handling, or low concrete strength, or uneven toe stress (limerock).
## BETA guidelines

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Uniform</td>
</tr>
<tr>
<td>80 - 100</td>
<td>Slight damage</td>
</tr>
<tr>
<td>60 - 80</td>
<td>Significant damage</td>
</tr>
<tr>
<td>&lt;60</td>
<td>Broken</td>
</tr>
</tbody>
</table>

*Capacity of broken piles is meaningless*
Capacity

- At time of testing
- vs depth during drive
- resistance distribution
  - CAPWAP ®
PDA testing
data interpretation

Easy driving

Hard driving
Pile as it encounters rock

Toe reflection in tension
(relatively easy driving)

Toe reflection in compression
(relatively hard driving)
**End of Drive**

- Low shaft resistance

**Restrike (8 days)**

- Increased shaft resistance
  (setup)
PDA testing

data interpretation

BOR 75D - 286 ton

BOR 1D - 189 ton

EOD 85 ton
Restrike testing - fine grained soils

Restrike testing generally undertaken 1 to 10 days after installation
Restrike testing - fine grained soils

Restrike testing generally undertaken 1 to 10 days after installation

Economically desirable

Technically desirable

Log time
1 Set up pile model and assume soil model for $R_{shaft}$ and $R_{toe}$

2 Apply one measured curve ($v_m$); Calculate complementary $F_c$

3 Compare $F_c$ with measured $F_m$

4 Adjust $R_{shaft}$ and $R_{toe}$

5 Go to step 2

Repeat until match is satisfactory
CAPWAP

CAPWAP match can be obtained by computer in fully automatic way!

First try (poor)

Final match (good)

Adjustments

..... is an iterative process
PDA testing + CAPWAP
leads to calculated load-set curve
Drilled Shaft Testing
Alternate: use hydraulic jaws

- **Drop weight**
- **Size**
- **drop mechanism**
- **Guides**
- **Cushion**
- **Pile preparation**
- **Sensor**
- **Attachment**
Loading guide

20 ton ram (free drop)

Static tests planned for 70 shafts (1.5 m OD) to 2000 tons

Westgate Freeway, Australia, 1982
30 ton drop weight
“APPLE” - A Preferred Pile Load Evaluator

“Big Newton” in honor of Sir Isaac’s F=ma
GRL drop hammer
(fuel pump removed from a diesel hammer)

Plywood cushion

Ohio
GRL drop hammer >
(fuel pump removed from a diesel hammer)
Drilled Shaft tests - Milwaukee Stadium

- CSL tests found 15 shafts with soft toes
- Capacity was questioned
- Quote for 2 static tests was $200,000
  $100,000 per test
- Quote for 15 PDA tests was $45,000
  $3,000 per test
- Client tested all 15 shafts with PDA
  total cost savings: $155,000
Drilled Shaft Testing in Milwaukee

Improvised Drop Hammer made on site: scrap steel bits in tube (not ideal, but it worked)

20 ton ram

Ram guide

Vibrator clamps to free release the ram

Vibrator support posts

Steel pin

42” drilled shaft

2000 ton Ru
Rult required
2000 ton
4000 kips

Ru = 4460.0 kips
Rs = 2886.8 kips
Rb = 1573.2 kips
Dy = .44 inch
Dmx = .44 inch
4 blows in PDA test in Milwaukee
(20 ton drop weight)

<table>
<thead>
<tr>
<th>BLOW NO.</th>
<th>DROP HEIGHT (ft)</th>
<th>RECORDED SET / BLOW (in)</th>
<th>TOTAL SET (in)</th>
<th>DISPLACEMENT (DMX) (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.5</td>
<td>0.03</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>0.02</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>0.02</td>
<td>0.06</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>0.02</td>
<td>0.08</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Rult required 2000 ton 4000 kips

<table>
<thead>
<tr>
<th>BLOW NO.</th>
<th>MAXIMUM FORCE (kips)</th>
<th>COMPRESSION STRESS (ksi)</th>
<th>TENSION STRESS (ksi)</th>
<th>ENERGY TRANSFER (ft - kips)</th>
<th>MOBILIZED CAPACITY (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2460</td>
<td>2.93</td>
<td>0.10</td>
<td>62</td>
<td>4230</td>
</tr>
<tr>
<td>2</td>
<td>3660</td>
<td>3.01</td>
<td>0.00</td>
<td>66</td>
<td>4460</td>
</tr>
<tr>
<td>3</td>
<td>4060</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4170</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stress OK
Rult OK
Milwaukee tests PIT done before and after PDA testing for every shaft. (2 examples shown)

PIT results show no damage to shaft due to PDA testing and improved toe bearing.
Conclusions,

**PDA testing on drilled shafts:**

- **proven worldwide application now**
- **uses available or easy-to-make drop hammers and minimal pile preparation**
- **confirms capacity, even at large loads**
- **reduced testing time and large cost savings**
  (cost 10 to 30 times less than static cost)
PDA Conclusions

• **PDA with CAPWAP evaluates capacity at low cost for driven piles, drilled shafts, & augercast piles**

• **PDA gives extra valuable information (integrity, stresses, hammer energy)**

• **PDA potentially saves time or pile length in favorable site conditions**

• **Improves quality control by more pile tests**
SPT Testing and Analysis

(Standard Penetration Test)
SPT Purpose:

- N-value (strength)
- Retrieve soil sample
### “Standard” Penetration Testing

#### “Non-standard” variables

<table>
<thead>
<tr>
<th>Category</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammers</td>
<td>Safety, Automatic, Donut</td>
</tr>
<tr>
<td>Operators</td>
<td>Manual, Semi-automatic, Automatic</td>
</tr>
<tr>
<td>Drill Rods</td>
<td>Size, Length</td>
</tr>
<tr>
<td>Lift Mechanisms</td>
<td>Cathead-rope, Cathead diameter, Spooling Winch, Chain Driven</td>
</tr>
<tr>
<td>Drill Methods</td>
<td>Hollow Stem Augers, Drilling Fluids</td>
</tr>
<tr>
<td>Split Tube Sampler</td>
<td>Shape, Liners or not</td>
</tr>
</tbody>
</table>
Why measure?

- Due to “non-standard” SPT systems, energy delivered can be highly variable
- Energy transfer affects N-value
- Soil strength estimated from N-value – (used in static analysis to estimate capacity)
- Obtain normalized N-value ($N_{60}$)
- Improve reliability of soil analysis
- Evaluate Liquifaction (ASTM D 6066)
## Energy Transfer

<table>
<thead>
<tr>
<th>Hammer Type</th>
<th>EFV avg</th>
<th>C.O.V</th>
<th>One std</th>
<th>Two std</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathead-rope</td>
<td>63</td>
<td>12</td>
<td>55 – 71</td>
<td>47 – 79</td>
<td>15</td>
</tr>
<tr>
<td>CME automatic</td>
<td>75</td>
<td>9</td>
<td>67 – 83</td>
<td>59 – 91</td>
<td>10</td>
</tr>
<tr>
<td>Spooling winch</td>
<td>35</td>
<td>8</td>
<td>31 – 39</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Hydraulic auto</td>
<td>69</td>
<td>15</td>
<td>59 – 79</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Donut</td>
<td>43</td>
<td>22</td>
<td>34 – 52</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Other Auto</td>
<td>49</td>
<td>13</td>
<td>42 - 56</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

*Data from GRL compiled by Utah State*
## Comparison of Studies

<table>
<thead>
<tr>
<th>Hammer</th>
<th>Study</th>
<th>EFV&lt;sub&gt;avg&lt;/sub&gt;</th>
<th>C.O.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Safety</strong></td>
<td>Utah State</td>
<td>63</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Flordia DOT</td>
<td>66</td>
<td>11</td>
</tr>
<tr>
<td><strong>Automatic</strong></td>
<td>Utah State</td>
<td>75</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Flordia DOT</td>
<td>80</td>
<td>8</td>
</tr>
</tbody>
</table>
**Normalized N value**

\[ N_{60} = \frac{N_m \times E_m}{\{ Wh \ (60\%) \}} \]

- **Wh (60%)** = Average Energy
- **\( N_m \)** = Measured N
- **\( E_m \)** = Measured Energy
Why measure on SPT?

- Energy is variable; affects N-value
- Soil strength estimated by N-value
  - (used in static analysis to estimate capacity)
- Obtain normalized N-value ($N_{60}$)

What is the benefit?

- Improves reliability of soil analysis
- Evaluate Liquifaction (ASTM D 6066)
Conclusions

- Great potential benefit to industry due to SPT testing
  - Better uniformity
  - Spot problem rigs
  - Improve predictions using N values
  - Adjust procedures to get uniform energy
The End