Pile Driving Analyzer® (PDA) and CAPWAP®

Proven Pile Testing Technology: Principles and Recent Advances

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Outline

- Introduction
  - The PDA History
  - Basics of PDA testing
  - Recent developments
- Wave Equation Analysis
- Stresses, damage prevention and detection
- Bearing capacity from CAPWAP and iCAP®
- Vibratory testing and analysis
- Dynamic pile testing and the LRFD approach
- Summary
Our Objective: to provide the necessary methods, hardware and software for reliable quality assurance of deep foundations
The Pile Driving Analyzer®
a long history of improvements

Conforms to ASTM D 4945
What is required?
Accurate, Reliable and Efficient Pile Top Force and Velocity Measurements

Reusable lightweight strain and acceleration transducers for testing any pile type
Transducers Requirements

- Accurately calibrated
- Rugged and Reliable
- Allow for self checking
- Adapt to any pile type
- Cost efficient
- Allowing for testing "after-the-fact" - when or if needed
Traditionally: 2 strain sensors + 2 accelerometers. But frequently we must use 4 strain sensors for accuracy! (large piles, spiral welded, all drilled shafts/piles, ...)

Transducer Placement
Smart, wireless Sensors

calibration transmitted with signal
Sensor-Transmitter Protection

- H-piles – no issue
Sensor-Transmitter Protection

- H-piles – no issue
- Pipe piles – use protectors
Lofting pile into leads

Sensors w/protectors

PDA
Sensor-Transmitter Protection

- H-piles – no issue
- Pipe piles – use protectors
- Concrete piles – protectors or sensors in indentations
Sensor-Transmitter Protection by Indentation
Engineer
- controls several PDAs simultaneously as if on-site
- monitors piles in real time
- reports within short time

Contractor
- schedules easily
- keeps project going
Design and Construction of Driven Piles*

- Soil Borings
- Static pile analysis
- Pile Type and Length selection
- Wave Equation analysis to check driveability
- Initial Pile Testing program by PDA
- Develop driving criterion
- Production pile installation to criterion
- Dynamic testing of production piles as needed

*See Hannigan et al., 2006. Manual on the Design and Construction of Driven Piles; FHWA
Wave Equation Analysis (GRLWEAP)

Thermodynamic model predicts stroke for diesels

Enter soil profile

Predicts Driveability
Wave Equation Analysis (GRLWEAP)

Updated hammer/driving system input

Updated soil parameters

Refined capacity vs. blow count after testing
Dynamic Pile Testing Objectives

• Finding optimal installation procedure with Dynamic Monitoring by Case Method for:
  • Hammer Performance
  • Driving Stresses
  • Pile Integrity
  • Soil Resistance at the time of testing

• Dynamic Load Testing:
  • Capacity vs. time EoD/BoR – setup/relaxation
  • CAPWAP® Signal matching
  • iCAP® Real time signal matching
Allowable Driving Stresses

Related to pile material strength

For Example, AASHTO provides the following limits:

- **Steel Piles** in Compression or Tension:
  90% of Steel Yield Strength

- **Prestressed Concrete Piles** in Compression:
  85% of concrete strength – Effective Prestress

- **Prestressed Concrete Piles** in Tension:
  Prestress + 50% of concrete tensile strength

- **Timber** - Southern Pine/Douglas Fir:
  3.2/3.5 ksi
Damage Detection

Example Records for a Spliced Pile

Good Pile: No early reflection

Bad Pile: Splice should not cause an early reflection
Toe Damage Detection: Early Record

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

F (2000) ——
V (7.7) ——

LS: 56.00 feet

TS: 51.2
TB: 28.8

WU (2000) ——
D (1.00) ——

LS: 56.00 feet

TS: 51.2
TB: 28.8

BN 220
Toe Damage Detection: First indication

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

F (2000)  V (7.7)  LS: 55.00 feet  A34 F34

TS: 51.2  TB: 28.8

WU (2000)  D (1.00)  LS: 55.00 feet

TS: 51.2  TB: 28.8  SET=0.218182 in

BN 260
**Toe Damage Detection: End of Drive**

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

**Image:**
- BS: 51.2
- TB: 28.8

**BS:** 51.2
**TB:** 28.8

**7 ft**

**BN 1094 - EOD**
CAPWAP - “Signal Matching”
State-of-practice; required by specs/codes

We know both Input and Response
(wave down and wave up)

This is the information needed to calculate
static and dynamic soil model parameters

- Always (to be) used for capacity calculation
  from dynamic load test
- Evaluates stresses vs. depth
- Models uniform or non-uniform piles
Pile and Soil Model

Pile Segment Impedance

\[ Z_i = E_i A_i / c_i \]

Spring (static resistance), i.e., Capacity and Distribution + Soil Stiffness

Dashpot (dynamic resistance)
CAPWAP Result Summary

[Graphs and data points for load and displacement, with specific values for different parameters such as force, embedment, and displacement.]
**Toe Dynamic Resistance: Measured and CAPWAP**


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**Fig. 5** (a) Measured pile top force and proportional velocity with CAPWAP computed top force: (b) Measured pile toe force with CAPWAP computed toe force.

**Fig. 6** (a) Measured static load test curve— with and without creep effects — and CAPWAP predicted load test curve: (b) Static test skin friction/end-bearing load distribution.
CAPWAP – Different Users, Static Test

CAPWAP Uniqueness? Pretty good
CAPWAP: Comparison with Static Tests

**CW versus SLT combined (N=303) (80, 96, SW)**

Unconservative (potentially unsafe)

Conservative (residual strength)

**Distribution of CW / SLT Ratios (96&SW: N=226)**

**Distribution of CW / SLTmax Ratios (96&SW: N=179)**

CAPWAP: Comparison with Static Tests

Conservative (residual strength)

Unconservative (potentially unsafe)
SC test data: T6P1 – 18 inch solid concrete pile

BOR 7 Day BN 4 (CAPWAP)  Static test (14D)

Dynamic: 180 k end bearing

Static: 176 k end bearing
# Superposition: When Restrike is Done with Insufficient Energy Thus not Activating Full End Bearing

<table>
<thead>
<tr>
<th>30 inch concrete pile</th>
<th>Blows/foot</th>
<th>Max. Trans Energy Kip-ft</th>
<th>Static Capacity, Kips</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Skin Friction</td>
</tr>
<tr>
<td>End of Drive</td>
<td>130</td>
<td>47</td>
<td>198</td>
</tr>
<tr>
<td>Static Load Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restrike</td>
<td>120</td>
<td>27</td>
<td>737</td>
</tr>
<tr>
<td>Superposition</td>
<td></td>
<td></td>
<td>737</td>
</tr>
</tbody>
</table>

* Not fully activated (low energy)

Considering Soil Setup Capacity

St. Johns River Bridge:

*Increased loads by 33% with substantially shorter piles (set-up considered)*

**Total project:**
- $110 million (actual)
- $20 million (savings)
- $130 million (estimate)

Scales & Wolcott, FDOT, presentation at PDCA Roundtable
Orlando 2004
iCAP®

Signal matching program, executed during monitoring, i.e., in real time, automatically, for immediate results.

Results:

- **Total Capacity, with distribution**
- **Load test curve**
- **Compression stresses (max and toe)**
- **Tension stress maximum**
- **Also: Case Damping factor and Match Quality**
iCAP on PDA

Sample data and results from a Pile Dynamics Inc. (PDI) iCAP on PDA device. The data includes measurements such as forces, moments, and velocities, along with specific values like F (1961), EMX, V (8.16), and TSC 0.0 MPa. The data is used to assess the performance of a pile installation and to ensure compliance with engineering standards.
iCAP comparison with CAPWAP (2010)

Pipe Piles

H-Piles

Concrete Piles
PDA Testing of Vibratory Driven Piles
PDA Testing of Vibratory Driven Piles

Measured - End of Driving

- Force - kN
- Velocity - m/s

Time - L/c (3.7 ms)

- Force
- Inertia
- Velocity
PDA Testing of Vibratory Driven Piles

- Soil resistance calculated from PDA force and velocity test results based on either power or force (Case Method) approach.

- Unfortunately, soil resistance and bearing capacity often differ significantly, thus impact restrike testing still necessary for dynamic capacity evaluation.

- GRLWEAP driveability predictions reasonable but sensitive to assumptions.
Load and Resistance Factor Design

AASHTO (2010): $\phi R_n \geq f_1 Q_1 + f_2 Q_2 + \ldots$

$\Phi = 0.50$ \hspace{1cm} wave equation analysis (no testing)

0.65 \hspace{1cm} 2\% or at least 2 dynamic tests

0.70 \hspace{1cm} several DOTs specs - dynamic

0.75 \hspace{1cm} static or 100\% dynamic tests

0.80 \hspace{1cm} static and 2\% dynamic tests
Example Calculation:

a) Assume 1.375 average load factor
b) Overall factor of safety: \( FS = \frac{1.375}{\varphi} \)
c) Assume \( R_n \) (nominal pile resistance) of 200 kips
Load and Resistance Factor Design

Calculating
Overall safety factor and
No. of piles required for a 2000-kip load

\[ \Phi = 0.50 \quad FS = 2.75 \quad R_n/FS = 72 \quad N_{\text{pile}} = 28 \]

<table>
<thead>
<tr>
<th>( \Phi )</th>
<th>FS</th>
<th>( R_n/FS )</th>
<th>N_{\text{pile}}</th>
</tr>
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<tbody>
<tr>
<td>0.65</td>
<td>2.11</td>
<td>95</td>
<td>21</td>
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<tr>
<td>0.70</td>
<td>1.96</td>
<td>102</td>
<td>20</td>
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<tr>
<td>0.75</td>
<td>1.83</td>
<td>109</td>
<td>18</td>
</tr>
<tr>
<td>0.80</td>
<td>1.72</td>
<td>116</td>
<td>17</td>
</tr>
</tbody>
</table>
Reasons for Dynamic Pile Testing

- We spend a lot on deep foundations in the USA: $4,000,000,000
- We want low risk of failure - remediation is expensive
- We want safe bridges and other structures
- With LRFD less risk translates into less cost
- Testing allows for optimizing a foundation
Summary: Pile Driving Analyzer

- Continuous improvements help obtain more information faster (wireless, remote) and at lower cost
- Test all pile types (steel, concrete, timber)
- Dynamic pile testing to supplement or replace static load tests
Summary: Pile Driving Analyzer

• Driving stress control to prevent damage
• Identify damaged piling
• Detect bad hammers for reliable application of driving criteria
• Economical dynamic testing allows for more tests and higher resistance factors
Summary: CAPWAP

- CAPWAP test analysis for reliable capacity prediction including resistance distribution and end bearing
- 40 years experience; large database
- Capacity at time of testing (EOD or BOR) for assessment of soil setup
- iCAP Signal Matching for operator independent and immediate results
Thanks for your attention

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www.pile.com