Embedded Data Collectors

Florida’s Experience Presented by:
Rodrigo Herrera, PE
Florida Department of Transportation
Asst. State Geotechnical Engineer

August 13, 2014
INTRODUCTION

- Majority of Florida bridges are supported on deep foundations
- Most common deep foundation: Precast Prestressed Concrete piles
- Dynamic testing of all Test Piles required as per Specifications
1995 FDOT PRACTICE

- Pile Installation Plan (Contractor)
- Pre-field wave equation analysis

- Test Pile program
  - Pile Driving Analyzer (PDA)
  - CAPWAP
  - Final wave equation
  - Driving Criteria

- Install Production Piles
DRIVING CRITERIA

- The Driving Criteria letter as a minimum addresses the following items;
  - Minimum number of blows per foot at various hammer stroke heights for the bearing layer
  - Maximum allowable stroke height
  - Minimum tip
  - Refusal conditions
  - Set-check requirements (when needed)
In 1996 we were asking WHAT IF?

• What if piles could be instrumented without climbing the leads?
• What if pile testing did not impact construction operations?
• What if all foundations could be monitored instead of issuing blow count criteria?
• What if all of this was affordable?
FDOT Sponsored Research

- Alternate dynamic testing method investigated by UF through FDOT sponsored research 1997-2002
- University of Florida’s Final report issued August 2002
  - Proposed theory
  - First generation hardware and software
EDC

EMBEDDED DATA COLLECTORS

FDOT Sponsored Research

- UF’s Research
  - Two levels of instruments cast into the pile, near the pile head and tip
  - Wireless transmission to a receiver in the field
FDOT Sponsored Research

- UF’s Research
  - Tip/skin ratio (using top & tip instruments)

\[
\text{Tip/Skin} = \frac{R_{D,\text{tip}}}{R_{D,\text{skin}}}
= \left[ F_{\text{down,tip}} + F_{\text{up,tip}} \right] / \left[ 2 * \left( F_{\text{down,tip}} - F_{\text{Down,tip}} \right) \right]
\]

\[
J_c = -0.09744 \ln \left( \frac{\text{Tip}}{\text{Skin}} \right) + 0.2686
\]
FDOT Sponsored Research

- UF’s Research
  - Case equation to estimate total static resistance

\[ \bar{R} = \frac{1}{2} [(1 - J_c)(F_1 + ZV_1) + (1 + J_c)(F_2 - ZV_2)] \]
FDOT Sponsored Research

- Unloading point used to estimate static end bearing

\[ F_{\text{applied}} = F_{\text{static}} + ma + cv \]

- Skin Friction = Total static minus static end bearing
FDOT Sponsored Research

- In 2003 Smart Structures, Inc. acquired a license to the patented technology
- Advancements to the software, hardware and signal transmission aspects of the system
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- Instruments cast into solid concrete piles;
- Two instrumentation levels, pile head and tip
CASTING PROCESS

• Instrumentation
  – Tip gages  
  – Connector cable (within the pile)  
  – Top gages and antenna
EMBEDDED DATA COLLECTOR

- **Signal conditioning, temperature sensor**
- **Accelerometer**
- **Strain transducer**

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CASTING PROCESS

ANTENNA TOP VIEW

Dataport Interface Cable (to radio module assembly)

Bottom surfaces of enclosure to be epoxy coated just prior to concrete casting per manufacturer's installation procedures.

ANTENNA SIDE VIEW

ANTENNA END VIEW

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CASTING YARD MEASUREMENTS

- Install two levels of instruments prior to casting the pile
  - Get an initial measurement to confirm signal transmission
  - Cast the pile
  - Subsequent measurements
    - Strain before and after cutting pre-stressing strands
    - Temperature readings at pile core and antenna (ambient)
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SOFTWARE INTERFACE

• Display of raw data;
  – Strain and acceleration
  – Qualitative assessment of data
SOFTWARE INTERFACE

- Display of top level instrumentation;
  - Force-Velocity
  - Wave up / Wave down
  - Pile static capacity
  - Compression and tension stresses
  - Estimates of pile integrity (MPI)
SOFTWARE INTERFACE

- Tip instrumentation readings;
  - Static force
    - Damping & inertia (unloading point)
  - Force-velocity at the tip of the pile
  - Measured compressive stress near the pile tip
## Embedded Data Collectors

**Embedded Data Collectors**

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August 13, 2014

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### User Information

- CEI Name
- Company Name
- City
- State
- Zip
- Certification ID
- Phone Number

### Project Information

- Project Name
- City
- State
- County/District
- Project Number (DOT)
- Project Description
- Structure
- Description
- Latitude
- Longitude

### Notes

Drive Duration From: 06-10-2013 12:23:21 to 06-10-2013 12:39:34

**Average at identified displacement unless a single blow or indicated otherwise in header (e.g. Tension)**

<table>
<thead>
<tr>
<th>Tip Elevation (Feet)</th>
<th>Blow Number</th>
<th>Blows per Foot to Disp</th>
<th>Stroke/BPM (Feet)</th>
<th>Energy (Kips-ft)</th>
<th>Fixed Jc Capacity (Kips)</th>
<th>UF Capacity (Kips)</th>
<th>Wave Speed (Feet/sec)</th>
<th>Top Compression (Ksi)</th>
<th>Tip Compression (Ksi)</th>
<th>Max Tension (Ksi)</th>
<th>MPI</th>
<th>Top Preload (uStrain)</th>
<th>Tip Preload (uStrain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-11.87</td>
<td>3</td>
<td>4</td>
<td>2.6</td>
<td>12.3</td>
<td>54.5</td>
<td>45.0</td>
<td>13003.4</td>
<td>1.1</td>
<td>0.2</td>
<td>0.7</td>
<td>87.5</td>
<td>-28.5</td>
<td>-75.0</td>
</tr>
<tr>
<td>-13.87</td>
<td>10</td>
<td>3</td>
<td>4.7</td>
<td>12.8</td>
<td>25.7</td>
<td>39.7</td>
<td>13111.7</td>
<td>1.1</td>
<td>0.2</td>
<td>0.7</td>
<td>100.0</td>
<td>2.8</td>
<td>-2.4</td>
</tr>
<tr>
<td>-14.87</td>
<td>13</td>
<td>3</td>
<td>4.7</td>
<td>12.3</td>
<td>61.0</td>
<td>64.7</td>
<td>13125.1</td>
<td>1.1</td>
<td>0.1</td>
<td>0.6</td>
<td>100.0</td>
<td>1.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>-15.87</td>
<td>16</td>
<td>3</td>
<td>4.7</td>
<td>12.2</td>
<td>64.3</td>
<td>62.7</td>
<td>13185.8</td>
<td>1.2</td>
<td>0.9</td>
<td>100.0</td>
<td>2.3</td>
<td>-3.0</td>
<td></td>
</tr>
<tr>
<td>-16.87</td>
<td>19</td>
<td>3</td>
<td>4.5</td>
<td>11.6</td>
<td>59.0</td>
<td>55.3</td>
<td>13188.0</td>
<td>1.1</td>
<td>0.2</td>
<td>100.0</td>
<td>2.0</td>
<td>-6.7</td>
<td></td>
</tr>
<tr>
<td>-17.87</td>
<td>22</td>
<td>3</td>
<td>4.5</td>
<td>11.0</td>
<td>42.3</td>
<td>37.3</td>
<td>13206.3</td>
<td>1.1</td>
<td>0.1</td>
<td>100.0</td>
<td>2.4</td>
<td>-4.7</td>
<td></td>
</tr>
<tr>
<td>-18.87</td>
<td>24</td>
<td>2</td>
<td>4.8</td>
<td>11.9</td>
<td>59.5</td>
<td>52.5</td>
<td>13223.7</td>
<td>1.1</td>
<td>0.1</td>
<td>100.0</td>
<td>1.9</td>
<td>-4.8</td>
<td></td>
</tr>
</tbody>
</table>
SOFTWARE OUTPUT

- UF and Fixed methods
- Minimum Tip
- NBR
SOFTWARE OUTPUT

- Top and Tip compressive stresses
- Max. Tension
CALCULATION METHODS

- Fixed Case Method
  - Constant damping factor for the entire drive, input by operator
  - Only top level of instruments
- UF Method
  - Damping factor is calculated for every hammer blow using pile top and tip measured data
CALCULATION METHODS

- UF Method – Continued
  - Allows for the separation of static and dynamic resistance in real time, no signal match analysis required on an instrumented pile (top & tip)
EVALUATING RESULTS

• Phase I, In-House evaluation (2006-2010)
  – Compare EDC estimates to PDA & CAPWAP;
• Phase II, UF (2009 – Present)
  – Collect results and generate a database of EDC vs. static load tests to develop a system-specific resistance factor for use in LRFD design
EVALUATING RESULTS

– Phase 1: Compare EDC to PDA and CAPWAP

• Database of piles monitored simultaneously with EDC and PDA

• EDC data was collected and reported by different engineers than those collecting the PDA data.
EDC EVALUATION – PHASE I

<table>
<thead>
<tr>
<th></th>
<th>Fixed/PDA</th>
<th>UF/PDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVG</td>
<td>0.99</td>
<td>0.95</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.089</td>
<td>0.101</td>
</tr>
<tr>
<td>COV</td>
<td>0.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>
## EDC/PDA Static Capacity

Population “n” = 213,734 blows from 139 piles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed Method/PDA</th>
<th>UF Method/PDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Median</td>
<td>0.93</td>
<td>0.91</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.17</td>
<td>0.18</td>
</tr>
</tbody>
</table>
EDC EVALUATION – PHASE I

Population “n” = 205,516 blows from 134 piles

<table>
<thead>
<tr>
<th>STRESS, ENERGY AND INTEGRITY</th>
<th>EDC/PDA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSX</td>
</tr>
<tr>
<td>Mean</td>
<td>0.92</td>
</tr>
<tr>
<td>Median</td>
<td>0.93</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.09</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.1</td>
</tr>
</tbody>
</table>
## EDC/CAPWAP STATIC CAPACITY

Population “n” = 78 blows from 78 piles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed Method/CAPWAP</th>
<th>UF Method/CAPWAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.88</td>
<td>0.86</td>
</tr>
<tr>
<td>Median</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.24</td>
<td>0.26</td>
</tr>
</tbody>
</table>
EDC EVALUATION - CAPWAP

![Graph showing the relationship between EDC and CAPWAP](image)

\[ y = 0.8896x \]

\[ R^2 = 0.889 \]
EDC EVALUATION - CAPWAP

Skin Static Capacity for version 3.761

- Linear (Trendline)
- Linear (Series2)

\[ y = 0.7757x \]
\[ R^2 = 0.5599 \]
EDC EVALUATION - CAPWAP

End Bearing Static Capacity for version 3.761

\[ y = 0.8561x \]

\[ R^2 = 0.7779 \]
TIP DAMAGE INDICATOR

![Graph showing Beta and Microstrain vs Blow Number]
TIP DAMAGE INDICATOR

- Changes in measured strain;
  - Observed more often near the tip of the pile
  - Gradual loss of pre-stress as a precursor to damage

Measured state of stress during driving
EVALUATING RESULTS

– Phase 2: Compare EDC to Static Load Tests
  • 18 results
    – 12 in Florida
    – 4 in Louisiana
    – 2 in North Carolina
EVALUATING RESULTS (2013)
EVALUATING RESULTS (2014)

- SLT did not reach Davisson resistance
- Re-strike performed 13 days prior to static load test
## IMPLEMENTATION

### Table 3.5.6-1  Resistance Factors for Piles (all structures)

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Loading</th>
<th>Design Method</th>
<th>Construction QC Method</th>
<th>Resistance Factor, $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven Piles with 100% Dynamic Testing</td>
<td>Compression</td>
<td>Davison Capacity</td>
<td>EDC or PDA &amp; CAPWAP</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EDC or PDA &amp; CAPWAP &amp; Static Load Testing</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EDC or PDA &amp; CAPWAP &amp; Static Load Testing</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Uplift</td>
<td>Skin Friction</td>
<td>EDC or PDA &amp; CAPWAP</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EDC or PDA &amp; CAPWAP &amp; Static Uplift Testing</td>
<td>0.65</td>
</tr>
<tr>
<td>Driven Piles with ≥5% Dynamic Testing</td>
<td>Compression</td>
<td>Davison Capacity</td>
<td>Driving criteria based on EDC or PDA &amp; CAPWAP</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Driving criteria based on EDC or PDA &amp; CAPWAP &amp; Static Load Testing</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Driving criteria based on EDC or PDA &amp; CAPWAP &amp; Static Load Testing</td>
<td>0.70</td>
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<tr>
<td></td>
<td>Uplift</td>
<td>Skin Friction</td>
<td>Driving criteria based on EDC or PDA &amp; CAPWAP</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Driving criteria based on EDC or PDA &amp; CAPWAP &amp; Static Load Testing</td>
<td>0.60</td>
</tr>
<tr>
<td>All piles (Extreme Event)</td>
<td>Lateral</td>
<td>FBPier$^1$</td>
<td>Standard Specifications</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Load</td>
<td></td>
<td>Lateral Load Test$^2$</td>
<td>1.00</td>
</tr>
</tbody>
</table>

1. Or comparable lateral analysis program.
2. When uncertain soil conditions are encountered.
**IMPLEMENTATION**

- Design Bulletins issued on 2006, 2009 and 2010 addressing the use of EDC in test and production piles
- Collect sufficient data to evaluate the system
IMPLEMENTATION

– July 2011 Workbook

• EDC introduced as a stand-alone system (Section 455-5.13)

Either install Embedded Data Collectors (EDCs) in the piles in accordance with Design Standards, Index No. 20602 or attach instruments (strain transducers to measure force and accelerometers to measure acceleration) with bolts to the pile for dynamic load testing.
IMPLEMENTATION

– 2014 Standard Specifications

455-5.11 Methods to Determine Pile Capacity:

455-5.11.1 General: Dynamic load tests using Embedded Data Collector (EDC) equipment and the UF Method of analysis, or an externally mounted instrument system and signal matching analyses will be used to determine pile capacity for all structures or projects unless otherwise shown on the Plans. When necessary, the Engineer may require static load tests to confirm pile capacities. When the Contract Documents do not include items for static load tests, the Engineer will consider all required static load testing Unforeseeable Work. Notify the Engineer two working days prior to placement of piles within the template and at least one working day prior to driving piles. Do not drive piles without the presence of the Engineer.

If the internally mounted system fails to communicate properly with the receiving system, allow the Engineer sufficient time to mobilize back-up equipment for performing dynamic load testing.
IMPLEMENTATION

– Cost

- EDC instruments: $899/pile
- Installation: $100 (standard top/tip)
- Workstation lease $995/month
- Software lease for office use $89/month, or $961/year
- Pile Installation monitoring (∼ $500/pile, assumes two piles driven per workday)

Contact Smart-Structures for details
POSSIBILITIES FOR THE FUTURE

(Tran et al., 2012)

Tip + Skin = Total (no need for Case Eq. or UP)
EDC EVALUATION

• Summary
  – Technology developed initially through FDOT funded research
    • UF - Dr. Michael McVay
  – Evaluation and stepped implementation of the system by FDOT between 2006 and 2011
EDC EVALUATION

• Summary
  – Top and tip gauges eliminate the need for signal matching
  – No climbing leads
  – Measured tip compressive stress
  – Measured loss of pre-stress, early warning of developing pile damage
Thank you

Rodrigo.Herrera@dot.state.fl.us