Embedded Data Collectors

Florida’s Experience
Presented by:
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Florida Department of Transportation
Asst. State Geotechnical Engineer

August 27, 2013
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
  - 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 for the use of two levels of instruments
  - First generation hardware and software
FDOT Sponsored Research

- In 2003 Smart Structures, Inc. acquired a license to the patented technology
- Advancements to the hardware and signal transmission aspects of the system
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EMBEDDED DATA COLLECTOR

- 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
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EMBEDDED DATA COLLECTOR

Signal conditioning, temperature sensor

Accelerometer

Strain transducer
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

Face of Concrete

ANTENNA END VIEW
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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Casting Yard Battery  Pile Driving Battery
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;
  – Measured compressive stress near the pile tip
  – Total, dynamic, inertial and static components of the measured force
  – Force-velocity
SOFTWARE OUTPUT

- Summary Table
  - Project information
  - Blows/ft
  - UF method (resistance)
  - Stresses
  - Energy
  - Stroke
  - Integrity
  - Other…

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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

Structure Pier 4
Pile Number 1
Pile Length 90
Pile Diameter 1
Set Check Marker Increment 1
Tip Gage to Pile Tip 24
Mid Gage to Pile Tip 0
Top Cross Section Area 575
Tip Cross Section Area 575
Modulus of Elasticity 5726.0567212
Concrete Specific Weight 0.16
Wave Speed 13300
Fixed Jc Damping Coefficient 0.8
Pile Tip Uplift Coefficient 0.96
Air Hammer/Impact False
Hammer SPI D46-32
Nominal Bearing Resistance 314
Tension Resistance 0
Minimum Tip Elevation -30
Jet/PreForm Elevation -10
Pile Cut-Off Elevation 16
Radio 1 ID 00 A0.8636.70.F2
Radio 1 FW Version 517
Final Tip Elevation -57.87

Notes

Drive Duration: From 00-18-2013 12:23:21 to 06-16-2013 12:35:34

**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>MP1</th>
<th>Top Preload Delta (uStrain)</th>
<th>Tip Preload Delta (uStrain)</th>
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SOFTWARE OUTPUT

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

• Top and Tip compressive stresses
• Max. Tension

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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)
  - Computes the contribution of end bearing and side friction to total resistance using both top and tip instrumentation.
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.
EVALUATING RESULTS

– Phase 1: Compare EDC to PDA and CAPWAP

- Neither engineer would see the other’s data until test pile program was completed and both reports turned in.
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EDC EVALUATION – PHASE I

<table>
<thead>
<tr>
<th></th>
<th>Fixed/PDA</th>
<th>UF/PDA</th>
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<tr>
<td>AVG</td>
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<td>STDEV</td>
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<td>COV</td>
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EDC EVALUATION – PHASE I

<table>
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<td>COV</td>
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EDC EVALUATION – PHASE I

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<th>EDC/PDA</th>
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<td>COV</td>
<td>0.11</td>
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</table>

embedded data collectors

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EDC EVALUATION – PHASE I

<table>
<thead>
<tr>
<th>EDC/PDA</th>
<th>AVG</th>
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<th>COV</th>
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<tr>
<td></td>
<td>0.90</td>
<td>0.423</td>
<td>0.47</td>
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</table>

Max Tension Stress (Ksi)

Blow Number

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EDC EVALUATION – PHASE I

Table:

<table>
<thead>
<tr>
<th>EDC/PDA</th>
<th>AVG</th>
<th>STDEV</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVG</td>
<td>0.98</td>
<td>0.084</td>
<td>0.09</td>
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</tbody>
</table>

Graph:

- Energy in Pile (Kips-ft)
- Blow Number

Lines:
- SmartPile
- PDA
EDC EVALUATION – PHASE I

Pile Integrity Estimate vs Blow Number

- **EDC/PDA**
  - AVG: 1.00
  - STDEV: 0.034
  - COV: 0.03

- **SmartPile (MPI)**
- **PDA (BTA)**
## 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>
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<td>Mean</td>
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<td>0.91</td>
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<tr>
<td>Median</td>
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<td>0.91</td>
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<td>Standard Deviation</td>
<td>0.15</td>
<td>0.16</td>
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<tr>
<td>Coefficient of Variation</td>
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<td>0.18</td>
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</table>
EDC EVALUATION – PHASE I

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

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<th>EDC/PDA</th>
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<td>Mean</td>
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<td>Median</td>
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<tr>
<td>Std. Deviation</td>
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<tr>
<td>Coefficient of Variation</td>
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</tbody>
</table>
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TIP DAMAGE INDICATOR

![Graph showing Beta and Microstrain vs. Blow Number]

- Beta
- Microstrain
- Blow Number

Legend:
- pda beta
- tip delta
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
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>
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<td>Mean</td>
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<td>0.86</td>
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<td>Median</td>
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<td>Standard Deviation</td>
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<tr>
<td>Coefficient of Variation</td>
<td>0.24</td>
<td>0.26</td>
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</tbody>
</table>
EDC EVALUATION - CAPWAP

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Total Static Capacity for version 3.761

EDC - FIXED METHOD (Kips)
CAPWAP (Kips)

Linear (Trendline)
Linear (One to One)

$y = 0.8911x$
$R^2 = 0.8907$
EDC EVALUATION - CAPWAP

![Graph showing Total Static Capacity for version 3.761]

- Linear (Trendline)
- Linear (One to One)

\[ y = 0.8896x \]

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

Skin Static Capacity for version 3.761

- Linear (Trendline)
- Linear (Series 2)

y = 0.7757x
R² = 0.5599

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EDC EVALUATION - CAPWAP

End Bearing Static Capacity for version 3.761

y = 0.8561x
R² = 0.7779

EDC - UF METHOD (Kips)
CAPWAP (Kips)
EDC EVALUATION – PHASE I

- Partial findings published in the proceedings of the 2009 International Foundation Congress and Equipment Expo
  - Blows with PDA estimate > 50 tons
  - Data within three standard deviations from the mean used in the development of statistical parameters
EVALUATING RESULTS

– Phase 2: Compare EDC to Static Load Tests
  • 12 Load Tests (7 compression and 5 tension)
    – 8 in Florida
    – 4 in Louisiana
    – More to come…
EVALUATING RESULTS

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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
– 2013 Standard Specifications
EDC EVALUATION

• Original Research
  – “Double wave up” for skin friction estimates
EDC EVALUATION

• Original Research
  – Tip to skin ratio

\[
\frac{\text{Tip}}{\text{Skin}} = \frac{[(F_b - ZV_b) - (F_c - ZV_c)]}{[(F_b - ZV_b) - (F_a - ZV_a)]}
\]
EDC EVALUATION

• Original Research
  – Case damping vs. tip/skin ratio

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

• Original Research
  – Case equation (Static resistance)

\[
\bar{R} = \frac{1}{2} \left[ \left( 1 - J_c \right) \left( F_1 + ZV_1 \right) + \left( 1 + J_c \right) \left( F_2 - ZV_2 \right) \right]
\]
EDC EVALUATION

- Original Research
  - Proposed method vs. static load tests
EDC EVALUATION

• Follow-up Research
  – Evaluate EDC’s measurements at the core of the pile vs. PDA and UF’s instrumentation measurements on the face of the pile under controlled laboratory conditions.
EDC EVALUATION

- Follow-up Research
EDC EVALUATION

• Follow-up Research
EDC EVALUATION

Figure 5-2. Comparison of peak $F_{up}$ between tip and top of pile.

Figure 5-3. Comparison of peak $F_{dw}$ between tip and top of pile.
EDC EVALUATION

- Implementation of Findings and Smart Structures Updates
  – Revised Tip/Skin ratio

\[
\text{Tip/Skin} = \frac{R_{D,\text{tip}}}{R_{D,\text{skin}}} = \frac{F_{\text{down,tip}} + F_{\text{up,tip}}}{2[F_{\text{down,\text{top}}} - F_{\text{Down,\text{tip}}}]}
\]
EDC EVALUATION

- Implementation of Findings and Smart Structures Updates
  - Unloading point method used for tip data analysis

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

- Possibilities for the future
  - New methods for both tip and skin friction determination from UF (Tran & McVay)
  - Monitoring throughout the lifetime of the structure
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

– Comparisons of total static capacity indicate that both UF and Fixed methods generally trend conservatively when compared to PDA and CAPWAP with averages near 86% and COV under 0.26
AASHTO-TIG

• Thank you

• Rodrigo.Herrera@dot.state.fl.us
Potential Future Benefits

Jc Determination without Signal Matching for the use of top gauges in production piles
INTRODUCTION

- The EDC’s UF method uses information from top and bottom gauges to determine the capacity of the pile without the need for signal matching analysis.

- This has one potential benefit: Obtaining Jc, Case damping value directly from the output without matching analysis.
INTRODUCTION

• Once Jc from top and tip instrumentation measurements is determined, it would be reasonable to use 100% EDC with top gauges only, similar to PDA.

• When we previously required 100% EDC on all projects, PDA and CAPWAP were used to determine Jc. Piles were then accepted based on the top gauge information.
Determining Jc

- The procedure is similar, except the EDC data and UF method are the basis for determining Jc.
- This is easily done when the Session Reports are loaded into Excel.
- A Session Report for each Jc value will need to be created and the comparison with the UF method performed in Excel.
EDC output

Here is a typical Session Report in Excel:
EDC output

The typical output includes “Fixed Jc Capacity” and “UF Capacity” columns:

![Table](image-url)
A column can be added to perform statistical comparisons between Jc Cap and UF Cap:

### EDC output

<table>
<thead>
<tr>
<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 Delta (uStrain)</th>
<th>Tip Preload Delta (uStrain)</th>
<th>Fixed Jc Cap/Uf</th>
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**Average at identified displacement unless a single blow or indicated otherwise in header (e.g. Tension)**

- Avg: 0.962
- std. Dev: 0.047
- cor: 0.999
- rmax: 1.103
- avg+ std: 1.010
The graphical output includes a chart comparing the Fixed Case capacity with Jc and UF capacity.

A typical output of an EDC session. In red, Jc capacity (at the JC value selected) compared with UF capacity (blue).
The value of \( J_c \) used in the Fixed Method analysis is called the Fixed \( J_c \) Damping Coefficient in SmartPile Review and can be changed. The user then replays the EDC data for each different \( J_c \) value.
Capacity variability in individual blows can also be seen by changing the Jc value.
Suggested Procedure

The EDC outputs may be used to estimate the Jc value as follows:

- Produce output data for several Jc values.
- Compare the values and plots of Fixed Jc Capacity and UF Capacity.
- Focus on data collected below the minimum tip elevation.
• Select the Jc value at which the Fixed Jc Capacity is closest to, but does not exceed the UF capacity

Note: The Fixed Jc capacity will not necessarily be parallel to the UF Capacity for the entire drive.

Example follows:
Jc=0.5 unconservative below El. -43.

Jc=0.6 is a good value. Great match and even slightly conservative below El -57.
Example 2:

- In this case it can be seen how a $J_c=0.6$ gives a very good match with the UF Capacity, throughout the full drive.
Notes on Set-Checks and re-drives

If the capacity is not achieved during initial drive, and we need a set-check (redrive) after a period of time, we may have a limitation because the Jc typically increases between initial drive and redrive, particularly in soils exhibiting set-up over time.