Evaluation of Static Design Resistance for Deep Foundations, FB-DEEP (BDV31 977-05)

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FB-DEEP Software Predicts Nominal Side ($R_s$), Tip ($R_T$) and Total ($R_N = R_s + R_T$) Resistance for Driven (steel H, Prestressed Concrete, and Steel Pipe) Piles and Drilled Shafts based on In situ data (SPT, CPT - piles) and laboratory (rock strength - drilled shafts); Used In FB-MultiPier for Substructure Pier Analysis and Design

FB-DEEP also identifies LRFD Design Resistances ($\Phi R_N$) for piles and shafts based on database of mean biases [measured nominal resistance (e.g. Davisson, FHWA) divided predicted resistance], and Coefficient of Variations (CV) of biases.
FB-DEEP PCP Prediction

Driven Pile Capacity: IDs 92-101

Curves:
- Ultimate Side Friction
- Mobilized End Bearing
- Ultimate Pile Capacity
- Estimated Davison Capacity
- Allowable Pile Capacity

Driven Pile Data:
- Boring Number: B-5
- Ground Surface Elevation: 15.72 (ft)
- Section: Square
- Width: 24.00 (in)

Project Data:
- File: Pile_Example1
- Date: Aug 03, 2015
- Engineer: Ahmed

Analysis Data:
- Analysis Type: SPT
Objectives of FB-DEEP Research

- For H piles, re-evaluate predicted side and tip resistances for piles driven through multiple layers of sand, clay and limestone;

- Evaluate side resistance for permanent cased drilled shafts in Limestone (FB-DEEP currently neglects);

- For prestressed concrete piles (PCP) re-evaluate side and tip resistance for piles driven into weathered (FHWA IGM – Intermediate Geotechnical Material) versus competent limestone (FB-DEEP currently treats both same);
## Collection of In Situ and Pile Data for FB-DEEP

**Sites with H Piles Evaluated in Florida:**

<table>
<thead>
<tr>
<th>Project Number (Financial)</th>
<th>Project Site</th>
<th># of Soil Borings</th>
<th>Predominant Soil Type</th>
<th>Dimensions (in)</th>
<th>Length (ft)</th>
<th># of Piles with CAPWAP</th>
<th># of BOR CAPWAP Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>208466-2-52-01</td>
<td>SR 51 from Taylor County Line to Dixie County Line</td>
<td>66</td>
<td>Sand &amp; Rock</td>
<td>14 x 89</td>
<td>60 - 120</td>
<td>3</td>
<td>1</td>
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<tr>
<td>221754-1-52-01</td>
<td>CR 146 over Aucilla River</td>
<td>9</td>
<td>Sand, Clay &amp; Rock</td>
<td>14 x 117</td>
<td>150 - 220</td>
<td>5</td>
<td>0</td>
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<tr>
<td>422796-1-52-01 &amp; 422796-2-52-01</td>
<td>Widening I 95 (SR 9) over Hallandale Beach Boulevard Bridge</td>
<td>5</td>
<td>Sand &amp; Rock</td>
<td>18 x 135</td>
<td>90 - 116</td>
<td>8</td>
<td>5</td>
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<tr>
<td></td>
<td>Widening I 95 (SR 9) over Hollywood Boulevard (SR 820)</td>
<td>3</td>
<td>Sand &amp; Rock</td>
<td>18 x 135</td>
<td>90 - 115</td>
<td>11</td>
<td>3</td>
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<tr>
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<td>Widening I 95 (SR 9) over Stirling Road (SR 848)</td>
<td>3</td>
<td>Sand &amp; Rock</td>
<td>18 x 135</td>
<td>110 - 168</td>
<td>5</td>
<td>4</td>
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<tr>
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<td>Widening I 95 (SR 9) over Pembroke Road Bridge</td>
<td>3</td>
<td>Sand &amp; Rock</td>
<td>19 x 135</td>
<td>85</td>
<td>9</td>
<td>6</td>
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<tr>
<td>403984-1-52-01</td>
<td>Eller Drive Overpass (SR 862)</td>
<td>29</td>
<td>Sand &amp; Rock</td>
<td>14 x 73</td>
<td>90 - 140</td>
<td>3</td>
<td>0</td>
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<tr>
<td>242484-2-52-01</td>
<td>I-4 (SR 408)/SR 408 interchange (Widening at Church Street Viaduct; Phase 1)</td>
<td>29</td>
<td>Sand &amp; Clay</td>
<td>14 x 89 &amp; 12 x 53</td>
<td>90 - 140</td>
<td>37</td>
<td>5</td>
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<tr>
<td></td>
<td>I-4 (SR 408)/SR 408 interchange (Widening over Robinson Street; Phase 2)</td>
<td>1</td>
<td>Sand</td>
<td>14 x 89</td>
<td>100 - 150</td>
<td>14</td>
<td>1</td>
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<tr>
<td></td>
<td>I-4 (SR 408)/SR 408 interchange (Widening over South Street; Phase 3)</td>
<td>2</td>
<td>Sand &amp; Clay</td>
<td>12 x 53</td>
<td>150</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Ramp E (Phase 4)</td>
<td>3</td>
<td>Sand &amp; Clay</td>
<td>14 x 89</td>
<td>150</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Ramp F2 (Phase 5)</td>
<td>5</td>
<td>Sand</td>
<td>14 x 89</td>
<td>105 - 135</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Ramps D &amp; D1 (Phase 6)</td>
<td>20</td>
<td>Sand &amp; Clay</td>
<td>12 x 53</td>
<td>90 - 115</td>
<td>18</td>
<td>1</td>
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<tr>
<td></td>
<td>Anderson Street Overpass &amp; Ramp F1 (Phase 7)</td>
<td>7</td>
<td>Sand &amp; Clay</td>
<td>14 x 89</td>
<td>---</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ramp C (Phase 8)</td>
<td>12</td>
<td>Sand</td>
<td>14 x 89</td>
<td>---</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>238429-3-52-01</td>
<td>US 27 (SR 50) Interchange at SR 50</td>
<td>7</td>
<td>Sand</td>
<td>14 x 73</td>
<td>99 - 120</td>
<td>33</td>
<td>18</td>
</tr>
</tbody>
</table>

| Total # of Soil Borings | 204 | Total # of CAPWAP Analyses | 171 | 45 |
Ultimate Unit Side Resistance: Current FB-Deep vs. New Curves

- Soil Type 1 - Plastic Clay (Current)
- Soil Type 1 - Plastic Clays & Silts (New)
- Soil Type 2 - Clay-Silt-Sand Mixtures (Current)
- Soil Type 2 - Clay-Silt-Sand Mixtures (New)
- Soil Type 3 - Clean Sand (Current)
- Soil Type 3 - Clean Sand & Clay-Silt-Sand Mixtures (New)
- Soil Type 4 - Soft Limestone & Very Shelly Sand (Current)
- Soil Type 4 - Soft Limestone & Very Shelly Sand (New)
Analysis of Tip Resistance for H Piles in FB-DEEP

**Clean Sand**

- FB-DEEP
- Proposed FB-DEEP
- US27 (18 piles)
- I-95 Pembroke
- I-95 Hollywood (1 pile)
- I-4 Ramp F1 (1 pile)

\[ q_t = \begin{cases} 
0.65N & \text{if } N < 20 \\
2N - 27 & \text{if } 20 \leq N < 40 \\
53 & \text{if } N \geq 40 
\end{cases} \]

**Soft Limestone**

- FB-DEEP
- Proposed FB-DEEP
- I-95 Hallandale
- I-95 Pembroke
- SR-51
- CR 146 over Auclia River
- Eller Driver

\[ q_t = \begin{cases} 
\frac{2N}{3} & \text{if } N < 30 \\
55 & \text{if } 30 \leq N < 60 \\
85 & \text{if } N \geq 60 
\end{cases} \]
- Total Capacity: **Current FB-Deep vs. CAPWAP**

  - Mean Bias = 1.18
  - StDev. = 0.34
  - CV = 0.29
  - N = 33

- Total Capacity: **Proposed FB-Deep vs. CAPWAP**

  - Mean Bias = 1.16
  - StDev. = 0.20
  - CV = 0.17
  - N = 33
H Piles Plug Conditions

- Difficulties in Matching Results with Measured Data
  1. Soil Borings
H Piles Plug Conditions

- Difficulties in Matching Estimates with Measured Data
  1. Soil Borings
H Piles Plug Conditions

- Difficulties in Matching Estimates with Measured Data
  1. Soil Borings

Contractor built a dirt road to get to the site
H Piles Plug Conditions

- Difficulties in Matching Estimates with Measured Data
  1. Soil Gaps (between the H Pile Flanges) have not been recorded

  3. Long term capacities are rarely evaluated (7-day RESTRIKE or longer)
  4. Static Load Tests not common
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H Piles Plug Conditions – Case Studies

1) Project in Progress HP 14x89 with 4.2-k Ram D19-42 Hammer

Variability in Soil Profiles
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Variability in PDA results
(Concrete Piles at the same site)
1) Project in Progress HP 14x89 with 4.2-k Ram D19-42 Hammer

Variability in PDA results
However, due to the averaging (8B+3.5B) and critical depth correction, all current FB-Deep curves looks quite similar, with all of them expecting 400 kips (required) at around elev. -70 ft. No curve is showing 500 to 700 kips at elev. – 50 to -56 ft.
1) Project in Progress HP 14x89 with 4.2-k Ram D19-42 Hammer

- RQ5 and Estimates (kips)
- RUC and Estimates (kips)

Approx Ground Elev (ft) = 15.5
Denting 10th Str 3V10-D0
Use: FB-Deep V2.04 Formulas
  Average End Bearing in EB zone
  \( N \text{ max} = 60 \)
  Gap to elev (ft) = 11
In vibrate zone, \( N60 \) values are 10.
Model: Partially Plug w/ Ultimate E.B.

Research boring done within 3-ft of Pile

Need to model the high capacity lens
H Piles Plug Conditions – Case Studies

1) Project in Progress HP 14x89 with 4.2-k Ram D19-42 Hammer

Research boring done within 3-ft of Pile

Need to model the high capacity lens
1) Project in Progress HP 14x89 with 4.2-k Ram D19-42 Hammer

Bent 1, Pile 5 experienced no hard limestone.

N limited to lower values to reflect the thin limestone shelves; Vibrated Zone also has great influence.
H Piles Plug Conditions – Case Studies

2) I-95 over Butler Blvd (Jacksonville) HP 14x89 with 6.6-k Ram D30-42 Hammer

Site is quite uniform

2 furthest borings are approx 200-ft apart

Borings closest to EB1 piles (within 100-ft)
H Piles Plug Conditions – Case Studies

2) I-95 over Butler Blvd (Jacksonville) HP 14x89 with 6.6-k Ram D30-42 Hammer
   - PDA results are similar among the piles

PDA Results of EB1, Pier 2, and EB3 piles (compared to prediction from boring B-1)
2) I-95 over Butler Blvd (Jacksonville) HP 14x89 with 6.6-k Ram D30-42 Hammer

Ultimate skin friction in layers
above bearing layer = 25.58(tons)

Average SPT in Bearing layer
above tip = 46.24(blow/ft)

Ultimate skin friction in
bearing layer = 30.77(tons)

Corrected Ultimate skin friction
in bearing layer = 18.08(tons)

Total Skin Friction = 43.66(tons)

End bearing capacity

ELEVATION SPT Blows UNIT E. B.
(ft) (Blows/ft) (tsf)

-34.41 26.57 28.34 <-- 8B above tip
-36.70 60.00 64.00
-39.20 49.60 52.91
-41.70 60.00 64.00
-44.20 60.00 64.00 <-- Pile tip elevation
-46.70 78.12 64.00
-48.48 54.22 52.30 <-- 3.5B below tip

Average unit end bearing above pile tip = 56.99(tsf)
Average unit end bearing below pile tip = 61.56(tsf)
Average unit end bearing of pile tip = 59.28(tsf)

Critical depth of embedment in bearing layer = 14.69(ft)
Actual depth of embedment = 12.50(ft)

Maximum mobilized end bearing capacity = 83.63(tons)
Corrected mobilized end bearing capacity = 74.68(tons)
2) I-95 over Butler Blvd (Jacksonville) HP 14x89 with 6.6-k Ram D30-42 Hammer

Predictions of 7 borings within 200-ft agree well with the PDA results from EB1, Pile 6
1) Let Engineers decide Upper Limit of SPT-N (not default to N=60). E.g. Limit of 60, 80, or 100
2) If the limestone shelves are thin, let Engineers select Upper Limit of says N = 30 or 35
3) Resistance should be included when N < 5. To be still conservative, this lower limit can be N<2 or N<3. However, it is best for the Engineers to select this Lower Limit as well
4) Gap should be included in the analyses
5) In the Vibrated Depth, let the Engineers decide to overwrite the SPT-N values (e.g. N=10)
6) Average 8B+3.5B zone and Critical Depth correction maybe suitable for other soil types, but may not be suitable for H piles due to its shape.
7) Current formulas (including recently proposed formulas) will need to be further evaluated to best fit the results at other analyzed sites.
8) It appears that the following 2 models best reflect the PDA EOD results:
   (i) “6-sided Side Resistance” plus “Box Mobilized End Bearing”
   (ii) “Partially Plugged Side Resistance” plus “Partially Plugged Ultimate End Bearing”
9) All other models produce much lower capacity predictions (compared to PDA EOD results)
10) For BOR (long term) capacity, let the Engineers enter the setup factors for each layer. FB-Deep will then have 2 curves: EOD and Longterm. Example: Sand (Soil 3) – $A_0 = 1$ to 1.2
    Silt (Soil 2) – $A_0 = 1$ to 1.5
    Limestone (Soil 4) – $A_0 = 1$ to 2
    Clay (Soil 1) – $A_0 = 1.2$ to 2
Victory Bridge Pier 52 Shaft 4
Side Friction of Cased Drilled Shafts in Limestone

Casing Ends Between Instrumentation

\[ f_{s,c} = \frac{P_1 - P'}{\pi D L_c} \]

\[ P' = P_2 + f_{s2} \pi D L' \]

\[ f_{s,1} = \frac{P_1 - P_2}{\pi D (L_c + L')} \]

\[ f_{s,2} = \frac{P_2 - P_3}{\pi D L_g} \]
<table>
<thead>
<tr>
<th>Project Site</th>
<th>Load Test Shaft</th>
<th>Load Test Method</th>
<th>Embedment Depth in Limestone (ft)</th>
<th>Diameter (ft)</th>
<th>Unit Skin Friction &amp; Displacement in Cased Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>First-Yield</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$f_s$ (tsf)</td>
</tr>
<tr>
<td>Pier 26 Shaft 2</td>
<td>O-cell</td>
<td>2.5</td>
<td>4</td>
<td>0.5</td>
<td>0.030</td>
</tr>
<tr>
<td>Pier 52 Shaft 3</td>
<td>Statnamic</td>
<td>1</td>
<td>4</td>
<td>1.7</td>
<td>0.340</td>
</tr>
<tr>
<td>Pier 91 Shaft 4</td>
<td>O-cell</td>
<td>2.5</td>
<td>4</td>
<td>1.69</td>
<td>0.850</td>
</tr>
<tr>
<td>Pier 26 Shaft 1</td>
<td>Statnamic</td>
<td>1</td>
<td>4</td>
<td>1.4</td>
<td>0.030</td>
</tr>
<tr>
<td>Bent 3 Shaft 2</td>
<td>O-cell</td>
<td>2.03</td>
<td>4</td>
<td>1.8</td>
<td>0.080</td>
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<tr>
<td>Bent 3 Shaft 1</td>
<td>O-cell</td>
<td>1</td>
<td>4</td>
<td>1.75</td>
<td>0.090</td>
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<td>Test Shaft #5</td>
<td>Statnamic</td>
<td>5</td>
<td>4</td>
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<td>Pier 4 Shaft 4-1</td>
<td>O-cell</td>
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<td>4</td>
<td>0.7</td>
<td>0.080</td>
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<tr>
<td>Pier 4 Shaft 4-2</td>
<td>O-cell</td>
<td>3.7</td>
<td>4</td>
<td>0.8</td>
<td>0.170</td>
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<td>Pier 5 Shaft 10</td>
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<td>10.33</td>
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<td>0.79</td>
<td>0.220</td>
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<td>Lee Roy Selmon</td>
<td>Test Shaft #3</td>
<td>Statnamic</td>
<td>4</td>
<td>1.8</td>
<td>0.400</td>
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<td>17th Street</td>
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<td>LTSO-1</td>
<td>O-cell</td>
<td>9.2</td>
<td>4</td>
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<td>LTSO-2</td>
<td>O-cell</td>
<td>18.5</td>
<td>4</td>
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<td>Apalachicola River</td>
<td>Pier 59, TS#8</td>
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<td>3</td>
<td>0.4</td>
<td>0.100</td>
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<td>Jewfish Creek</td>
<td>Test Shaft #1</td>
<td>Statnamic</td>
<td>2</td>
<td>0.5</td>
<td>0.022</td>
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<td>Test Shaft #2</td>
<td>Statnamic</td>
<td>2.5</td>
<td>0.75</td>
<td>0.037</td>
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</tbody>
</table>

7 Sites, 16 Cased Drilled Shafts in Limestone
Side Friction of Cased Drilled Shafts in Limestone

\[ f_s = 0.1 \times (c \times \text{Rec}) \text{ tsf} \quad \text{when } c \times \text{Rec} \leq 12 \text{tsf} \]

\[ f_s = 1.2 \text{ tsf} \quad \text{when } c \times \text{Rec} > 12 \text{tsf} \]

\[ c = \frac{1}{2} \sqrt{q_u \sqrt{q_t}} \]
Sites with Prestressed Concrete Piles Evaluated in Florida:

<table>
<thead>
<tr>
<th>Site Information</th>
<th>Insitu Information</th>
<th>Pile Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Number (Financial)</td>
<td># of Soil Borings</td>
<td>Predominant Soil Type</td>
</tr>
<tr>
<td>242484-2-52-01 I-4/SR 408</td>
<td>58</td>
<td>Sand</td>
</tr>
<tr>
<td>210448-2-52-01 San Sebastian Bridge</td>
<td>11</td>
<td>Sand &amp; Clay</td>
</tr>
<tr>
<td>211449-1-52-01 CR 229 over South Prong of St. Mary's River</td>
<td>2</td>
<td>Sand &amp; Clay</td>
</tr>
<tr>
<td>209293-2-52-01, 209294-1-52-01, SR 98</td>
<td>121</td>
<td>Sand &amp; Rock</td>
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<tr>
<td>208166-1-52-01 Plantation Oaks Boulevard over SR 23</td>
<td>50</td>
<td>Sand &amp; Rock</td>
</tr>
<tr>
<td>208466-2-52-01 SR 51</td>
<td>6</td>
<td>Clay &amp; Rock</td>
</tr>
<tr>
<td>420809-3-52-01 I-595</td>
<td>234</td>
<td>Sand &amp; Rock</td>
</tr>
<tr>
<td>213304-3-52-01 I-95 Overland Bridge Replacement</td>
<td>133</td>
<td>Sand &amp; Rock</td>
</tr>
<tr>
<td>406813-6-52-01 CR 245 over Olustee Creek</td>
<td>10</td>
<td>Sand &amp; Rock</td>
</tr>
<tr>
<td>210687-3-52-01 SR 200 North of Callahan</td>
<td>11</td>
<td>Clay &amp; Rock</td>
</tr>
<tr>
<td>429551-1-52-01 SR 200 South of Callahan</td>
<td>31</td>
<td>Sand &amp; Rock</td>
</tr>
<tr>
<td>422796-1-52-01 &amp; 422796-2-52-01 I-95 over Snake Creek</td>
<td>5</td>
<td>Sand &amp; Rock</td>
</tr>
</tbody>
</table>

Total # of Soil Borings: 672  
Total # of Piles with CAPWAP Data: 684  
Total # of Piles with Limestone Bearing Layer: 264  
Total # of BOR CAPWAP Analyses on Piles with Limestone Bearing Layer: 65
Analysis of PCP in weathered & Competent Limestone

Unit Side Friction:

Weathered Limestone with mixtures
Weathered Limestone with clean sand
Competent Limestone
Current FB-DEEP Clay-silt-sand mixtures
Current FB-DEEP Clean sand
Current FB-DEEP Limestone

Weathered

Competent

$y = 0.0768x$
$R^2 = 0.756$

$y = 0.0314x + 0.0005$
$R^2 = 0.617$

$y = 0.0297x - 1.0283$
$R^2 = 0.5389$
Analysis of PCP in weathered & Competent Limestone

Unit End Bearing (Average N – 8B below):

Currently Adding Palmetto Expressway, District 6 (19 Bridges PCP in Limestone)
Thank You